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Terra Vac In situ Vacuum Extraction System Applications Analysis Report

Foster Wheeler Enviresponse, Inc., Livingston, NJ

Prepared for:

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16. ABSTRACT

This report analyzes the results from the SITE Program's 56-day demonstration at the Valley Manufactured Product Company's site in Groveland, Massachusetts. Conclusions were reached concerning the technology's suitability for use in remediations involving both similar and different materials at other sites.

Operational data and sampling and analysis information were monitored carefully to establish a database against which vendor's claims for the technology could be evaluated. Additional data on the technology's performance at other sites is also discussed.

The conclusions from the results of the Groveland demonstration test and from other available date are: (1) the process can be used to remediate a site contaminated with VOC's; (2) the process can remove VOC's from soils with permeabilities as low as 10^{-8} cm/s; (3) the process operates well in all weather conditions; and (4) the process implementation costs can be as low as $20/ton, depending on various site-specific conditions.

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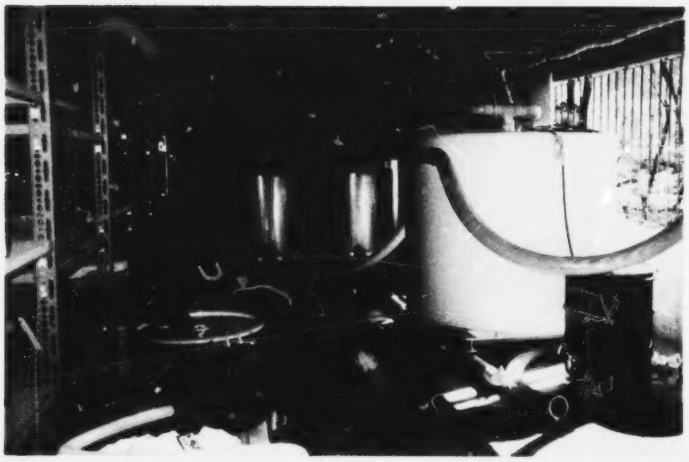

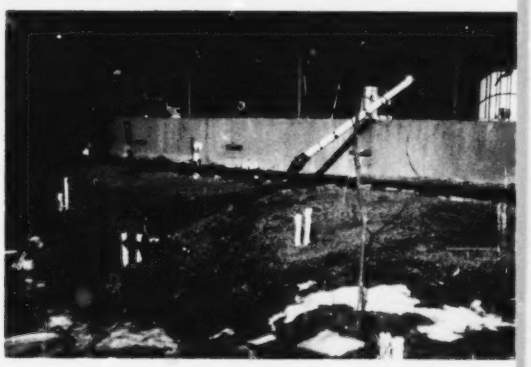

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EPA/540/A5-89/003
July 1989

Terra Vac In Situ Vacuum Extraction System

Applications Analysis Report

Risk Reduction Engineering Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, OH 45268

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Notice

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Foreword

The Superfund Innovative Technology Evaluation (SITE) program was authorized in the 1986 Superfund amendments. The program is a joint effort between EPA's Office of Research and Development and Office of Solid Waste and Emergency Response. The purpose of the program is to assist the development of hazardous waste treatment technologies necessary to implement new cleanup standards which require greater reliance on permanent remedies. This is accomplished through technology demonstrations which are designed to provide engineering and cost data on selected technologies.

This project consists of an analysis of Terra Vac's in situ vacuum extraction process, which was demonstrated on the property of an operating machine shop. The property is part of the Groveland Wells Superfund Site in Groveland, Massachusetts. The demonstration effort was directed at obtaining performance and cost information which would be useful for assessments at other sites. Documentation will consist of two reports. The Technology Evaluation Report (EPA/540/5-89-003a) describes the field activities and laboratory results. This Applications Analysis provides an interpretation of available data and discusses the potential applicability of the technology.

Additional copies of this report may be obtained at no charge from EPA's Center for Environmental Research Information, 26 West Martin Luther King Drive, Cincinnati, Ohio, 45268, using the EPA document number found on the report's front cover. Once this supply is exhausted, copies can be purchased from the National Technical Information Service, Ravensworth Bldg., Springfield, VA, 22161, (702) 487-4600. Reference copies will be available at EPA libraries in their Hazardous Waste Collection. You can also call the SITE Clearinghouse hotline at 1-800-424-9346 or 382-3000 in Washington, D.C. to inquire about the availability of other reports.

Margaret M. Kelly, Director
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Program Management and
Technology

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Office of Environmental Engineering
and Technology Demonstration

Abstract

This document is an evaluation of the Terra Vac in situ vacuum extraction system and its applicability as a treatment method for waste site cleanup.

This report analyzes the results from the Superfund Innovative Technology Evaluation (SITE) Program's 56-day demonstration at the Valley Manufactured Product Company's site in Groveland, Massachusetts and data from other applications. Conclusions were reached concerning the technology's suitability for use in remediations involving both similar and different materials at other sites.

Operational data and sampling and analysis information were monitored carefully to establish a database against which vendor's claims for the technology could be evaluated.

The conclusions from the results of the Groveland demonstration test and from other available data are: (1) the process can be used to remediate a site contaminated with VOCs; (2) the process can remove VOCs from soils with permeabilities as low as 10^{-8} cm/s; (3) the process operates well in all weather conditions; and (4) the process implementation costs can be as low as $10/ton, depending on various site-specific conditions.

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Abbreviations and Symbols

API	American Petroleum Institute
ARAR	Applicable or Relevant and Appropriate Requirements
ASTM	American Society for Testing and Materials
BDAT	Best Demonstrated Available Technology
BNA	base neutral/acid (extractable)
BTEX	benzene, toluene, ethylbenzene, and xylenes
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CFR	Code of Federal Regulations
cm/s	centimeters per second
CDM	Camp, Dresser, McKee, Inc.
CWA	Clean Water Act
DCA	1,2-dichloroethane
DCE	trans 1,2-dichloroethylene
DCB	dichlorobenzene
DMF	dimethyl formamide
ECD	electron capture detector
EPA	Environmental Protection Agency
EP Tox	Extraction Procedure Toxicity Test
EW	extraction well
FDER	Florida Dept. of Environmental Regulation
FID	flame ionization detector
ft^3	cubic feet
GC/MS	gas chromatograph/mass spectrometer
g/ml	grams per milliliter
gmol	gram mole
HSWA	Hazardous and Solid Waste Amendments to RCRA - 1984
kPa	kilopascal (s)

Abbreviations and Symbols (Continued)

kW	kilowatt(s)
LDR	land disposal restriction
m/s	meters per second
MEK	methyl ethyl ketone
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
MIBK	methyl isobutyl ketone
MW	monitoring well
NCP	National Contingency Plan
N/m	Newtons per meter
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
O&G	oil and grease
ORD	Office of Research and Development
OSHA	Occupational Safety and Health Act
OSWER	Office of Solid Waste and Emergency Response
PAHs	polycyclic aromatic hydrocarbons
PCE	tetrachloroethylene
PL	Public Law
ppb	parts per billion
ppm	perts per million
ppmv	parts per million by volume
ppmw	parts per million by weight
PRP	potentially responsible party
psi	pounds per square inch
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act of 1976
RI/FS	Remedial Investigation/Feasibility Study
ROD	Record of Decision
RREL	Risk Reduction Engineering Laboratory
SARA	Superfund Amendments and Reauthorization Act of 1986
scfh	standard cubic feet per hour

Abbreviations and Symbols (Continued)

SITE	Superfund Innovative Technology Evaluation
TCA	1,1,1-trichloroethane
TCE	trichloroethylene
TCLP	Toxicity Characteristic Leaching Procedure
TCP	1,2,3-trichloropropane
THF	tetrahydrofuran
TOC	total organic carbon
TRI	1,1,1-trichloroethane
TSCA	Toxic Substances Control Act of 1976
UCS	unconfined compressive strength
µm	micrometer
µg/L	micrograms per liter
UST	underground storage tank
VES	vacuum extraction system
VOC	volatile organic compound
yd^3	cubic yard

Conversions

	English (US)	Metric (SI)
Area:	1 ft^2	9.2903×10^{-3} m^2
	1 in^2	6.4516 cm^2
Flow Rate:	1 gal/min	6.3090×10^{-5} m^3/s
	1 gal/min	6.3090×10^{-2} L/s
	1 Mgal/d	43.8126 L/s
	1 Mgal/d	3.7854×10^{3} m^3/d
	1 Mgal/d	4.3813×10^{-2} m^3/s
Length:	1 ft	0.3048 m
	1 in	2.54 cm
	1 yd	0.9144 m
Mass:	1 lb	4.5359×10^{-2} g
	1 lb	0.4536 kg
Volume:	1 ft^3	28.3168 L
	1 ft^3	2.8317×10^{-2} m^3
	1 gal	3.7854 L
	1 gal	3.7854×10^{-3} m^3

ft = foot, ft^2 = square foot, ft^3 = cubic foot
in = inch, in^2 = square inch
yd = yard
lb = pound
gal = gallon
gal/min = gallons per minute
Mgal/d = million gallons per day
m = meter, m^2 = square meter, m^3 = cubic meter
cm = centimeter, cm^2 = square centimeter
L = liter
g = gram
kg = kilogram
m^3/s = cubic meters per second
L/s = liters/sec
m^3/d = cubic meters per day

Acknowledgments

This report was prepared under the direction and coordination of Mary Stinson, EPA SITE Program Manager in the Risk Reduction Engineering Laboratory - Cincinnati, Ohio. Contributors and reviewers for this report were Mr. James Ciriello of EPA Region I - Remedial Project Manager for the Groveland Superfund site at the time of the project; John Kingscott from the Office of Solid Waste and Emergency Response; Greg Ondich from the Office of Research and Development; James Malot, Ed Malmanis, and Neil Janis from Terra Vac Corp.; and Patrick Ford and James Thomas from Alliance Technologies, Inc.

This report was prepared for EPA's Superfund Innovative Technology Evaluation (SITE) Program by Peter A. Michaels of Foster Wheeler Enviresponse, Inc. for the U.S. Environmental Protection Agency under Contract No. 68-03-3255.

Section 1
Executive Summary

Terra Vac, Inc.'s in situ vacuum extraction process has been employed at several Superfund and non-Superfund sites. Available data from four sites where field activity has occurred, including three Superfund and one UST site, were reviewed and are summarized in Appendix D of this report.

Conclusions

The following conclusions, regarding applications of the technology, were drawn from reviewing the data on the Terra Vac in situ vacuum extraction process, both from the SITE Demonstration Test and other available data (Appendices C and D):

- The process represents a viable technology to fully remediate a site contaminated with volatile organic compounds (VOCs).

- The major considerations in applying this technology are the contaminant compound's volatility, site soil porosity, and the site-specific cleanup level.

- The process demonstrated good performance in removing VOCs from soil with measured permeability ranging between 10^{-4} and 10^{-8} cm/s. In practical terms, the process works well with most soil types. It was determined that air-filled porosity of a soil is a more important factor than permeability in the application of this technology.

- It is important where soils of low permeability and high moisture content, i.e. low air-filled porosity, are encountered that a pilot demonstration test be considered to determine the feasibility of dewatering the soil.

- The process operated well in all weather conditions. There had been concerns raised on its applicability during extreme winter conditions. The technology is relatively simple and should be considered reliable.

- Chemicals with Henry's Constant greater than 0.001 (dimensionless), see Table A-3, have been successfully extracted by the Terra Vac process. The process successfully extracted not only VOCs but also less-volatile hydrocarbons such as gasoline, diesel fuel, kerosene, and heavy naphthas. Henry's Constant is the parameter that can be used to determine whether a particular contaminant has sufficient volatility to be extracted by the process.

- The economics of this process strongly depend on whether off-gas treatment is required and whether any wastewater is generated at a site. This latter cost element can add as much as 20% to the total cost.

- Based on available data, the treatment costs are typically near $50/ton. Costs can be as low as $10/ton and for a small urban spill site as high as $150/ton. For a large remediation project, when no off-gas treatment is required and no wastewater is generated, the remediation cost can be less than $10/ton.

The vacuum extraction technology offers an economical option to remediate sites contaminated with volatile organics. Even when a contaminated site contains semivolatile organics and heavy metals in addition to VOCs, it may still be economical to first remove the volatile organics using vacuum extraction technology and then use other remediation technologies to remove, immobilize, or destroy the remaining contaminants after they have been excavated.

Discussion of Conclusions

The Terra Vac in situ vacuum extraction process was tested and evaluated under the Superfund Innovative Technology Evaluation (SITE) Program at the Valley Manufactured Products Co.'s machine shop in Groveland, Massachusetts. The site is part of the Groveland Wells Superfund site and was apparently contaminated by a leaking storage tank and by previous improper practices in the storage and handling of waste oils and solvents. The SITE Demonstration was conducted from December 1, 1987 to April 26, 1988. The major objectives of the SITE project were to collect data on performance, cost, and reliability to help support the above

conclusions, and to investigate procedures which could be used to predict the time required to achieve site remediation by attempting to cleanup a relatively small part of the total site during a 56-day period.

The demonstration project primarily consisted of sampling around four extraction wells which were constructed at the site. Three of the wells were designed as a barrier to isolate the fourth well by intercepting contamination from the larger source area. Testing consisted of extensive wellhead gas monitoring and soil sampling which occurred before, during, and at the end of the vacuum extraction activity. The data show wellhead gas concentrations decrease exponentially with time. The rate of decrease varied for the different wells. Due to the pattern of contamination, one of the barrier wells actually became isolated from the larger area of contamination and the adjacent soil was cleaned to a far greater extent than the other three wells.

Calculations were made to check a theoretical relationship between wellhead concentrations and surrounding soil levels. The calculated values were lower than actual soil concentrations by at least an order of magnitude. Thus, although wellhead gas levels are easier to measure, care should be exercised when they are used as a surrogate for the actual soil concentration.

Before one can attempt to make a rough estimation of the remediation time for a site, a target value for the particular contaminant in the remediated soil must be known. For the demonstration this target concentration is calculated by using two mathematical models, the Vertical and Horizontal Spread Model and the Organic Leachate Model. These mathematical models are used by EPA to evaluate petitions to the Agency for delisting wastes contaminated with VOCs. The mathematical models allow the use of a regulatory standard for drinking water, in order to arrive at a target soil concentration.

Once the target soil concentration is determined, a rough estimation of the remediation time can be made by taking a site-specific empirical ratio of soil concentration to wellhead gas concentration, and extrapolating to obtain a wellhead gas concentration at the target soil concentration. As an example, the calculated target soil concentration for the Groveland site is 500 ppbw. This corresponds to an approximate wellhead gas concentration of 89 ppb for one of the extraction wells (EW1S). The equation correlating wellhead gas concentration with time is then solved to give an approximate cleanup time of 150 days.

After this time period, the vacuum extraction system can be run intermittently to see if significant increases in gas concentrations occur on restarting, after at least a two-day stoppage. If there are no appreciable increases in gas concentration, the soil has reached its residual equilibrium contaminant concentration, and the system may be stopped and it is recommended that soil borings be taken and analyzed.

An example of a full-scale cleanup is a site remediation by Terra Vac at the Upjohn Facility Superfund site in Barceloneta, Puerto Rico, where the VOC concentrations in soils were reduced to levels below the detection limit of 5 ppb of CCl_4 from initial concentrations as high as 2,200 ppm. The site had a 300-ft-deep vadose zone, consisting mostly of clay soils. The site was considered remediated by EPA when nondetectable levels of CCl_4 in the wellhead gas were demonstrated for a period of three consecutive months. The vacuum extraction operations at this site remediated a total of 7,000,000 yd^3 in 3 years. If incineration were used to complete this remediation in the same timeframe it would require a capacity of 7,000 ton per day and would be impractical and uneconomical.

Operation of the process during the winter poses no problems as long as care is taken to prevent freezing in the system piping and valves by the application of electrical tracing and insulation. The actual process of vacuum extraction is unaffected by outside ambient temperatures, since subsurface temperatures generally do not vary by more than 10°F from summer to winter. Water extraction rates at Groveland were high during the winter because of thawing of the snow cover.

Terra Vac treatment costs generally range between $10 and $50 per ton with isolated instances of small urban spill sites as high as $150 per ton. The Groveland 56-day demonstration costs, modified to eliminate sampling and analytical costs not normally incurred by Terra Vac, amounted to $47 per ton. An estimate was made on a complete remediation of the portion of the site occupied by the demonstration. The complete remediation time was projected to be 150 days and the resulting cost amounted to $66/ton. Terra Vac's own estimate of the complete remediation of the entire Valley Manufactured Products Co. portion of the Groveland site was just under $39 per ton. The Terra Vac estimate was not that far removed from the EPA estimated costs and reflects the economy of scale. The quantity at the entire site is approximately 20,000 tons, whereas the demonstration treated 6,000 tons.

Section 2
Introduction

The SITE Program

In 1986, the EPA's Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) established the Superfund Innovative Technology Evaluation (SITE) Program to promote the development and use of innovative technologies to clean up Superfund sites across the country. Now in its third year, the SITE Program is helping to provide the treatment technologies necessary to implement new federal and state cleanup standards aimed at permanent remedies, rather than quick fixes. The SITE Program is composed of two major elements: the Demonstration Program and the Emerging Technologies Program.

The major focus has been on the Demonstration Program, which is designed to provide engineering and cost data on selected technologies. To date, the demonstration projects have not involved funding for technology developers. EPA and developers participating in the program share the cost of the demonstration. Developers are responsible for demonstrating their innovative systems at chosen sites, usually Superfund sites. EPA is responsible for sampling, analyzing, and evaluating all test results. The result is an assessment of the technology's performance, reliability, and cost. This information will be used in conjunction with other data to select the most appropriate technologies for the cleanup of Superfund sites.

Developers of innovative technologies apply to the Demonstration Program by responding to EPA's annual solicitation. To qualify for the program, a new technology must have a pilot or full scale unit and offer some advantage over existing technologies. Mobile technologies are of particular interest to EPA.

Once EPA has accepted a proposal, EPA and the developer work with the EPA regional offices and state agencies to identify a site containing wastes suitable for testing the capabilities of the technology. EPA prepares a detailed sampling and analysis plan designed to thoroughly evaluate the technology and to ensure that the resulting data are reliable. The duration of a demonstration varies from a few days to several months, depending on the type of process and quantity of waste needed to assess the technology. While it is possible to obtain meaningful results in a demonstration lasting one week using an incineration process, where contaminants are destroyed in a matter of seconds, this is not the case for a physical treatment such as the Terra Vac process where contaminants are extracted from the earth over long periods of time. In order to be able to make good extrapolations of the data, it was necessary that the Terra Vac demonstration test last for a duration of two months. After the completion of a technology demonstration, EPA prepares two reports, which are explained in more detail below. Ultimately, the Demonstration Program leads to an analysis of the technology's overall applicability to Superfund problems.

SITE Program Reports

The results of the SITE Demonstration program are incorporated in two basic documents, the Technology Evaluation Report and the Applications Analysis Report. The former provides a comprehensive description of the demonstration and its results. The likely audience will be engineers responsible for a detailed evaluation of the technology relative to a specific site and waste situation. These technical evaluators will want to understand thoroughly the performance of the technology during the demonstration, and the advantages, risks, and costs of the technology for the given application.

The Applications Analysis Report is directed at decision-makers responsible for selecting and implementing specific remedial actions. This report provides information in order to determine if the technology merits further consideration as an option in cleaning up specific sites. If the candidate technology described in the Applications Analysis appears to meet the needs of the site engineers, a more thorough analysis of the technology based on the Technology Evaluation Report and information from remedial investigations for the specific site will be made. In summary, the Applications Analysis will assist in the determination of whether the specific

technology should be considered further as an option for a particular cleanup situation.

Purpose of the Applications Analysis Report

Each SITE demonstration will evaluate the performance of a technology while treating the particular waste found at the demonstration site. Additional data from other projects will also be presented.

Usually the waste at other sites will differ in some way from the waste tested. Waste characteristic differences could affect waste treatability and use of the demonstrated technology at other sites. Thus, successful demonstration of a technology at one site does not assure that a technology will work equally well at other sites. The determination of the total operating range over which the technology performs satisfactorily will be made by examining, not only the demonstration test data, but other data available from field applications of the technology.

To enable and encourage the general use of demonstrated technologies, EPA will evaluate the applicability of each technology to sites and wastes in addition to those tested, and will study the technology's likely costs in these applications. The results of these analyses will be distributed through the Applications Analysis Report.

Key Contacts

Information useful to potential technology users can be provided by the following sources:

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Section 3
Technology Applications Analysis

Introduction

This section of the report addresses the applicability of the Terra Vac In Situ Vacuum Extraction Process to remediate various sites contaminated with various volatile organic compounds, based on the results of the SITE demonstration test and other Terra Vac test results data.

Since the results of the demonstration test provide the most extensive database, conclusions on the effectiveness and its applicability to other potential cleanups will be strongly influenced by those results, which are presented in detail in the Demonstration Report. Additional information on the Terra Vac technology, including a process description, vendor claims, a summary of the Demonstration Test results, and case studies of other applications are provided in Appendices B-D.

Conclusions

Following are the overall conclusions on the Terra Vac technology. These conclusions were drawn from a review of the existing data on the Terra Vac process:

- The process removes VOCs from soils of low, as well as high, permeability.
- The process represents a viable technology for fully remediating a site contaminated with VOCs.
- The major factors to be considered in applying the technology are contaminant volatility, site soil porosity, and the site-specific cleanup level.
- Declining VOC recovery rates correlated well as an exponential function of time of treatment. This makes it possible to estimate cleanup times.
- The process operates well in all weather conditions.
- The process costs are typically near $50/ton but can be as low as $10 per ton of soil treated.

Discussion of Conclusions

Soil Permeability

Terra Vac claims that the vacuum extraction technology will remove volatile organic compounds from virtually all hydrogeological settings including clays, silts, sand and gravel, alluvium, colluvium and glacial till, wetlands, and fractured rock and karst (see Appendix B). The SITE program demonstration of the Terra Vac process in Groveland, Mass. showed that it was possible to remove VOCs from clays having a permeability of 10^{-8} cm/s. The Groveland results (see Appendix C) showed considerable reductions in TCE levels in certain clay strata; at a certain location (MW 3) they were reduced from 200-1,600 ppm TCE before the test to ND-60 ppm TCE after the test. The largest site to date at which Terra Vac has completed operations is the Upjohn Facility Superfund Site in Barceloneta, Puerto Rico (see Appendix D-1). This site has a 300-ft-deep vadose zone with soil formations that are mostly clay having hydraulic conductivities of 10^{-7} cm/s. The action involved the vacuum extraction from the vadose zone of a carbon tetrachloride spill. Terra Vac had a portion of this site to remediate, and almost all soil samples that were taken at the completion of a 2 1/2-year-run were below the detection limit of 5 ppb CCl_4. Terra Vac is in the process of remediating the Tyson's Dump Superfund Site in Upper Merion Twp., Pa., which has a hydrogeology of clay and silty sands. At Tyson's Dump, Terra Vac installed more than 100 wells at varying depths and is using four vacuum blowers for the job -- two 700-hp machines, and two 500-hp machines. They are using an onsite activated-carbon regeneration-system employing steam for regeneration, and packed-tower air-water stripper for the treatment of contaminated groundwater that is extracted by the vacuum system.

The pore size for clays is small, offering a large resistance to the flow of liquids and a much lower resistance to the flow of the smaller air molecules. For vacuum extraction to work well, the soil must have a reasonable value for the air filled porosity so that the induced stripping air may have a low

resistance to flow. It was found that the total porosities of the soils at the Groveland site, whether they were sands, silty sands or clays, were approximately the same. As long as the water content of the soil is not too high, there would be enough air-filled porosity. As an example, if the total porosity is measured at 50% and the moisture content is 20%, the calculation of air-filled porosity, using a bulk density of the soil of 1,761 kg/m^3, would be:

Total porosity = 0.5 = fraction of total volume occupied by pores
For 1 m^3 of soil, 0.5 m^3 is occupied by pores
For 1 m^3 of soil, there is 0.2x1,761 = 352.2 kg H_2O content
Volume of H_2O = 352.2 kg x 1 m^3/1,000 kg = 0.3522 m^3
Volume of air = 0.5 - 0.3522 = 0.1478 m^3
Air-filled porosity = 14.78%

The above calculated value of air-filled porosity is for the Groveland site and the value obtained was high enough to achieve good vacuum extraction. If, for the same total porosity and bulk density, the moisture content was 28.4%, the air-filled porosity would be zero and the soil matrix would have to be dewatered in order to start the extraction process for VOCs. This type of dewatering can actually be done by the Terra Vac system, but it may extend the time required by the remediation.

Contaminant Volatility

Theory tells us that the vacuum extraction process can remediate a site contaminated with VOCs, and that it is just a matter of time before this can be accomplished. The basis for successful application of vacuum extraction to clean up soils and associated interstitial water is Henry's Law. Simply stated, Henry's Constant is the ratio of a compound's concentration in air divided by the concentration in water. Compounds with higher Henry's Constants will clean up faster. Effective recovery of chemicals with Henry's Constants greater than 0.001 (dimensionless) have been demonstrated by Terra Vac.

Site-Specific Cleanup Levels

For the contaminant trichloroethylene (TCE), successful petitions for delisting have been made to EPA, where the Agency has applied the mathematical models for delisting to come up with a level of 0.59 ppm. For the purpose of this study it was assumed that the Groveland Superfund site could be considered remediated if the soil residual TCE concentration is 0.59 ppm or lower. The actual ROD for the Groveland site, which selected a combination of vacuum extraction and groundwater stripping as the remedial technology for the site, did not set a soil concentration target. It is reasonable to assume, given the results of the demonstration (see Appendix C) that this level may be reached for this site if there were enough extraction wells and enough vacuum pumps installed to do the job. The results in the small demonstration area indicate that the test area may be remediated within about 150 days.

Terra Vac has remediated the Upjohn Facility Superfund Site, and has accomplished this in a 2 1/2-year time frame on a site with clay soils. The Groveland site data show a steady decline in the recovery rate over time, and were correlated using an exponential equation of the form $y = ae^{-kx}$, where y = concentration of contaminant in extracted vapors and x = time. From these data it is possible to estimate the time required to achieve a desired contaminant concentration in the extracted vapors.

Estimation of Remediation Time

The relationship between the contaminant concentration in the extracted vapors and the soil concentration value is not known with any reasonable degree of certainty and should be assumed as site-specific. This is important because although measurements of the extracted vapor contaminant levels are relatively easy to make, the SITE demonstration showed that they cannot assume to represent the soil concentrations. One must analyze a series of soil borings (this has been done in the Groveland SITE program), and then determine by analysis what the concentration in the wellhead extracted vapors was when the soil borings were taken. Then a gross extrapolation may be made to see what the wellhead concentration would be at the desired remediated soil concentration (see Appendix C).

This will only be a rough estimation of the time required for remediation. It is important to know how long the process is to continue running before it may be stopped and the soils tested. The vacuum extraction process exhibits higher contaminant concentration levels of the extracted vapors when starting up after a shutdown of a few days. When the soil is close to reaching its residual equilibrium concentration, or when the vacuum extraction process is effectively not removing any more contamination, this increase in concentration will not occur upon startup after a prolonged shutdown. It is recommended that the vacuum extraction process be run intermittently after reaching the time calculated by the foregoing rough estimation method. The final soil borings may be taken if the residual equilibrium concentration is reached.

Reliability

The Terra Vac system in Groveland operated in the winter during severe weather conditions. The entire

piping system from the extraction wells to the equipment was electrically heat traced to prevent freeze-ups, which would otherwise occur, especially during brief shutdowns. The snow cover on the site offered no interference with air induction in the Terra Vac process, even though Terra Vac does not use air injection wells. During the winter at Groveland more groundwater was extracted by the process because of thawing of the snow cover.

Siltation caused a blockage and cessation of the vacuum extraction process in one of the deep wells (EW4D) during the second half of the demonstration period. Attempts to clear the blockage by pulse-pumping water down the well during the mid-test break were unsuccessful. When siltation of a well occurs causing a blockage it is usually necessary to drill a new well adjacent to the blocked one.

The Terra Vac vacuum extraction system may be left unattended for long periods of time except when activated-carbon canister replacement becomes necessary. The degree of operator attention required is a function of the size and the complexity of the project. A project the size of the Groveland demonstration may require no-one for long periods of time whereas the Tyson's Superfund site, which has an activated carbon regeneration facility and a water treating facility in addition to about 100 extraction wells requires 20 people during the daytime.

Costs

Typical costs for vacuum extraction systems depend on a number of site-specific factors including: the size of the site, the nature and amount of the contamination and the hydrogeological setting (see Section 4). For a large site, for example 100,000 ton with sand soil and a contaminant such as TCE the implementation costs may be $10 per ton. For small sites, such as 10,000 yd^3 with clay soils and TCE contaminant, the cost might be $50/ton.

Application of Vacuum Extraction Technology

Vacuum extraction of volatiles and semivolatiles is favorable for a wide variety of applications including:

- Source control
- Assessment of source areas
- Emergency response
- Liquid-phase recovery
- Enhanced groundwater treatment
- In situ or ex situ processes

As a safer, more-cost-effective, and permanent alternative to excavation and disposal, vacuum extraction provides effective source control of contaminants in soils. Also, whereas excavation is disruptive and may be impractical due to physical conditions at the site -- such as depth, location of buildings, roadways or utilities, and the proximity to residents -- vacuum extraction has been successfully implemented under buildings, industrial tank farms, gas stations, and beneath large diameter (150 ft) above-ground storage tanks.

Studies have shown that the process of soil excavation can release 60% to 90% of the volatile contaminants into the atmosphere, even where engineering controls are in place. Accordingly, volatiles rapidly released from the process of excavation, could violate air emissions regulations, cause unnecessary health risks to workers and to people in nearby residences, and cause nuisance odors. One significant advantage of the vacuum extraction process is that soils and groundwater are treated in situ, without excavation.

However, if excavation is required, treatment of volatiles can be handled effectively using a process known as "heap vacuum extraction". In this process, contaminated soils are placed on a treatment pad consisting of a horizontal, covered vacuum system. All of the volatiles remaining in the soil are extracted by essentially air stripping the soils in a controlled system. Thus, volatiles in soils are removed and treated.

Vacuum extraction technology may be used to delineate the extent and magnitude of VOC sources. Vacuum extraction wells can be installed and vapors extracted during site assessment. Since the extracted vapors represent a volume of soil that is much larger than that indicated by soil sampling, the extent and magnitude of the source area is thereby better quantified than by soil sampling alone. In addition, remediation can begin immediately if any contaminants are extracted.

In emergency response situations, rapid deployment of vacuum extraction can remove VOCs from soils before contaminants reach the aquifer. Rapid elimination of the residual contaminants in the vadose zone using vacuum extraction will minimize the impact of contaminants on groundwater quality.

Treatment of vapors produced by the process are typically handled in one of three ways: dispersion, carbon adsorption, or thermal destruction. Other methods -- such as condensation, biological degradation, ultraviolet oxidation, and others -- have been applied, but only to a limited extent. Dispersion often renders the vapors harmless. Quite often, the health risks posed by resultant concentrations in the air are much less severe than those posed by groundwater or contaminated soils. Methods that destroy the contaminants are preferable, but they do increase costs. Destruction by thermal incineration

or catalytic oxidation is quite effective, especially for hydrocarbons. Chlorinated hydrocarbons can be effectively treated by thermal destruction or adsorbed by activated carbon. Regeneration of the spent carbon on site is preferred to landfilling, so that chemicals adsorbed on the carbon can either be recycled or destroyed.

Vacuum extraction is a safe process with minimal permitting required to implement a system. Since all contaminants are under vacuum until treated, the possibility of a release is virtually eliminated. Many states require an air permit for operation of the vacuum extraction process. However, compliance with even the strictest regulations is easily within the capability of the technology.

Equipment used in the Terra Vac process can be either mobile or fixed equipment. Typically, the leasing of mobile extraction units is more cost effective than capitalizing onsite equipment, since cleanup is so rapid compared to common equipment amortization schedules. Mobilization of Terra Vac's portable equipment can be accomplished within about one week, with startup and full-scale operations within about two weeks. Operation and maintenance costs are minimal and the Terra Vac system has demonstrated its ability for safe, unattended, continuous operation.

Environmental Regulation Requirements for the Technology

This section discusses briefly the environmental regulations that pertain to hazardous waste remediations. The discussion focuses on the restriction on land disposal of hazardous wastes and the use of the in situ vacuum extraction technology for Superfund actions.

The Resource Conservation and Recovery Act (RCRA)

The Resource Conservation and Recovery Act (RCRA) was enacted on October 21, 1976, and was amended in 1980 and 1984. The amendments of 1984 are called the Hazardous and Solid Waste Amendments (HSWA).

There are nine subtitles that comprise RCRA, and the subtitles that pertain to the cleanup of hazardous wastes are:

- Subtitle C - Hazardous Waste Management System
- Subtitle D - State and Regional Solid Waste Plan
- Subtitle I - UST Regulations

Congress took a position in the HSWA to ban the land disposal of untreated hazardous wastes. Deadlines were established by Section 3004 of HSWA covering the restriction of untreated hazardous-waste disposal into landfills. EPA developed treatment standards for the first deadline of November 8, 1986 covering both spent solvent waste listed by EPA and listed dioxin wastes. Treatment standards for the second deadline of July 8, 1987 covered a group of mostly liquid hazardous wastes identified by the California Department of Health Services or "California list wastes". "California list wastes" include corrosive wastes, wastes containing metals and cyanides, and halogenated organics. EPA developed treatment standards for the first third of its list of hazardous wastes on August 6, 1988. EPA has deadlines of June 8, 1989, for the second third of that list and May 8, 1990, for the final third.

Treatment standards are based on the performance of the BDAT to treat the waste. A technology is considered to be demonstrated for a particular waste if the technology is in full-scale commercial operation for treatment of that waste. Treatment standards can be established either as a specific technology or as performance standard based on a BDAT. When treatment standards are fixed at a performance level, the regulated community may use any technology not otherwise prohibited to treat the waste so that it meets the treatment standard.

Since the Terra Vac technology is an in situ treatment, it does not involve the placement of hazardous waste. Therefore, land ban requirements do not apply. However, residuals which are generated from the treatment of restricted RCRA hazardous waste are themselves considered as restricted RCRA hazardous waste. Therefore, residuals such as activated carbon and recovered water may be subject to the land ban requirements in the future.

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

Statutory Requirements

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986, provides for federal funding to respond to releases of hazardous substances to air, water, and land. CERCLA authorized EPA to prepare the National Contingency Plan (NCP) for hazardous substance response. The NCP defines methods and criteria for determining the appropriate extent of removal, remedy, and other measures. Specific techniques mentioned in the NCP for remedial action at hazardous waste sites include in situ treatment as a

cost-effective technology for handling contaminated soil and sediment.

Section 121 of SARA, entitled Cleanup Standards, strongly recommends remedial actions using treatment that "...permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances." The actions must assure protection of human health and the environment, meet ARARs, be in accordance with the NCP, and be cost-effective. This means that when selecting an appropriate remedial action, the first step is to determine the level of cleanup that is necessary to protect the environment, and the second step is to choose the most cost-efficient means of achieving that goal. SARA further states that "offsite transport and disposal...without such treatment should be the least favored alternative remedial action where practical treatment technologies are available."

SARA also added a new criterion for assessing cleanups that includes consideration of potential contamination of the ambient air. This is in addition to general criteria requiring that remedies be protective of human health and the environment. Since vacuum extraction involves the collection of contaminated vapors, all these criteria must be considered in assessing appropriate levels of air treatment.

Superfund Response Actions

Superfund response actions must meet "applicable or relevant and appropriate requirements" (ARARs) for remediation. Land disposal restrictions (LDRs) may be "applicable or relevant and appropriate" to Superfund actions. LDRs are applicable when existing federal or state laws can be used to have direct authority over placement of restricted hazardous wastes in, or on, the land. LDRs may be relevant and appropriate when Superfund hazardous substances are sufficiently similar to restricted industrial hazardous wastes such that use of LDRs is suited to the circumstances of the releases.

In addition to industrial process waste, the HSWA also addresses soil and debris that result from CERCLA response actions and RCRA corrective actions. Effective August 8, 1988, EPA issued a national capacity variance through November 8, 1990 for all CERCLA/RCRA soil and debris, which are contaminated with hazardous wastes whose BDAT standards are based on incineration.

In the meantime, the EPA intends to develop separate BDAT treatment standards for soil and debris, because the BDAT standards were developed for industrial waste processes, which are often different from the soil or debris waste matrices in terms of chemical/physical composition, concentrations, and media within and among sites.

Until standards are developed for soil and debris, remedies will continue to be selected on a site-specific basis. Since these remedies are not likely to conform to the BDAT standards for industrial process waste, a variance is often required.

Since vacuum extraction is an in situ process (no excavation and placement is involved) the land ban restrictions are not applicable. Individual states may however have rules or regulations affecting cleanup levels for a particular VOC contaminant in soil. Cleanup levels will be established on a site-specific basis.

In addition there are contaminated residuals that may result from the application of this technology. These include recovered groundwater and spent activated carbon from offgas treatment. Contaminated water requires treatment in accordance with the State National Pollution Discharge Elimination System permit levels prior to surface water discharge, or in accordance with pretreatment requirements prior to sewage discharge. Spent activated carbon should be disposed in accordance with the Agency's Offsite Disposal Policy.

Materials Handling Required by the Technology

Since this is an in situ process, the soil itself is not excavated for treatment. There are, however, various related activities that do involve the handling of material.

The construction of the extraction and monitoring wells requires the mobilization of a portable drill rig. If soil borings are required for analysis, they are obtained during the construction of the wells by hammering a split spoon into the ground, generally every two feet, before the soil is augered out. Soil tailings from the drilling operation are drummed and are usually disposed of offsite by incineration. The grout mix and bentonite for the construction of the wells are in bags and are mixed and poured by hand into the boring holes are supplied by the drilling contractor.

When offgas treatment is required and activated carbon canisters are used, the canisters employed are skid mounted so that they can be moved by using a fork lift truck. When contaminated groundwater is recovered by the vacuum extraction process, it can usually be disposed of by treating with carbon adsorption or with an air stripper and discharging on site. If this is not permitted, the contaminated water can be pumped into a holding tank. This holding tank can then be emptied by a tank truck that will

periodically haul the contaminated wastewater to a disposal facility.

Personnel Issues

The number of people involved in the operations of a Terra Vac installation is dependent on the size of the installation. For the Groveland site one person, working only during the day, was employed. During construction at Groveland, Terra Vac employed three people during the day for a period of almost two weeks. A large scale project, such as Tyson's (see Appendix D) would require a full-scale construction force while the project is being built. Tyson's required three people per shift during the normal operating period. All personnel must pass the appropriate physical examinations and have certificates of completion of an approved 40-hour hazardous materials training course as per the requirements of 29 CFR 1910.

Testing Procedures

The description of the sampling and analytical procedures used in the demonstration test is in Appendix C. For most jobs, it will not be necessary to employ all the tests specified therein. The most important tests are:

- Pretreatment soil boring VOCs by purge-and-trap GC/MS.
- Posttreatment soil boring VOCs by purge-and-trap GC/MS.
- Periodic VOC analysis in wellhead gas and activated carbon offgas by GC/FID or ECD.

Section 4
Economic Analysis

Introduction

A primary purpose of this economic analysis is to attempt to estimate costs (not including profits) for a commercial-size remediation using Terra Vac technology. It was expected that, where applicable, vacuum extraction technologies would be less expensive than most other technologies, such as incineration. Terra Vac technology has already been applied successfully at numerous Superfund and non-Superfund sites. Complete cost data could not be obtained from any of these applications. Therefore, this analysis is based on the partial remediation of part of the Groveland Superfund site during the SITE Demonstration. The demonstration test run lasted 56 days and the total amount of contaminated soil treated was estimated to be 6,000 tons. Thus, the base case (Case 1) in Table 4-1 represents the actual costs incurred during the demonstration.

Case 2 in Table 4-1 represents the estimated costs for complete remediation of the 6,000-ton portion of the Groveland site. The time necessary to achieve complete remediation was estimated from the use of actual data taken during the demonstration in the theoretical models that have been developed by Terra Vac and discussed in detail in Appendix C of this report. It was estimated that it would take 150 days (as per Appendix C) to accomplish the remediation. Since the combined offgas treatment and wastewater disposal costs represent the largest fraction of the total cost, assumptions had to be made in estimating these for Case 2 calculations.

Many costs were incurred at the Groveland site during the demonstration that do not typically occur in a commercial application. Therefore, such costs were not included in the analysis presented here. Permitting and regulatory costs were not included. Site preparation costs were primarily limited to the costs associated with drilling wells. In general, all cost elements that are normally associated with the use of this technology are addressed and an attempt is made to develop all the costs to be incurred by those responsible for the remediation of a site.

Results of Economic Analysis

The result of the analysis shows a cost-per-ton range of $27 to $66. The lower value is based on the Groveland site demonstration costs, but assuming that the technology is applied at a site where no offgas treatment is required and no wastewater is generated for disposal. Terra Vac has applied their technology at a number of both Superfund and non-Superfund sites where that has been the case. At the Barceloneta Superfund site, no offgas treatment was required and after the initial operation, no wastewater was generated. At the Groveland site, this cost element represented approximately 43% of the total costs.

The second major cost element associated with this technology is the cost of analyses. Pretest and posttest soil analyses should be performed at all sites. In addition, periodic wellhead-gas and stack-gas analyses are required. The costs for wellhead and stack-gas analyses are directly proportional to the operating time at a site, and thus may be site-specific.

At the Groveland site, the analytical costs were estimated to be 38% of the total cost for the demonstration, and 31% of the total cost for the full remediation case. Unfortunately, similar cost information was not available from any of the other sites at which the Terra Vac system has been used.

All the remaining costs associated with the use of the Terra Vac technology constitute between 20-25% of the total costs. In actual terms, based on the Groveland site analysis, these ranged from $9/ton to $15/ton. Clearly, these costs are strongly (but not linearly) dependent on the operating time required at a site.

The costs estimated in this report are higher than those normally claimed by Terra Vac. It should be noted that a number of cost elements, such as the maintenance of a field laboratory trailer and the adherence to strict QA/QC procedures, are either not

Table 4-1. Estimated Cost, $/Ton [a,c]

	Case 1 Demonstration 56 days	Case 2 Complete remediation 150 days
Site preparation	2.83	2.83
Permitting and regulatory	---	---
Equipment		
Terra Vac, $ (b)	50,000	50,000
Contingency (10% of direct costs)	0.28	0.56
Startup and fixed cost		
Operations procedures/training	0.40	0.40
Mobilization and shakedown	0.84	0.84
Depreciation (10% of direct costs)	0.28	0.56
Insurance & taxes (10% of direct costs)	0.28	0.56
Labor costs	2.77	6.93
Supplies - Raw materials	---	---
Supplies - Utilities		
Electricity	0.40	1.08
Effluent treatment	12.83	19.25
Residual disposal	7.50	11.25
Analytical		
During operation	1.44	3.86
Pretest and posttest analyses	16.66	16.66
Facility modifications		
(10% of direct costs)	0.28	0.56
Site demobilization	0.33	0.33
TOTALS	47.12	65.67

(a) This cost analysis does not include profits of the contractors involved.
(b) Not used directly, but is used for the estimate of other costs.
(c) The American Association of Cost Engineers defines three types of estimates: order of magnitude, budgetary,and definitive. This estimate would most closely fit an order of magnitude estimate with an accuracy of +50% to -30%.

charged to Terra Vac or not included in the estimated costs. Thus, if all these costs were included, or if the final remediation time turned out to be greater than the estimated 150 days, the final cost of remediation could be even higher.

The size of the remediation project can have a significant impact on the $/ton values. The analytical costs on a $/ton basis could be reduced significantly for a large site. For a large site at which no offgas treatment is required and no wastewater is generated, the cost of remediation could be as low as $10/ton.

Based on some sketchy cost information available from Bellview Superfund site (Appendix D-2), the cost of remediation ranged between $20 and $60 per ton, depending on the estimate of the amount of contaminated soil at the site.

Site-Specific Factors Affecting Cost

Vacuum extraction economics is very highly site-specific and is difficult to quantify exactly without the benefit of data from an accurate site-remedial investigation report. The factors most affecting cost include:

- size of site
- type of soil
- nature of contamination
- amount of contamination
- requirements for offgas treatment
- wastewater generation possibilities

Size of Site

A large site gives the process the benefit of economy of scale. Equipment costs, analytical costs, labor costs, and startup and fixed costs, all in $/ton, will decrease with a larger site. A larger site may be larger vertically, horizontally, or both. For the vacuum extraction technology, it is preferable to have a deeper vadose zone than one that is spread out. For the same volume of soil treated, a shallow vadose zone requires more wells to be drilled and constructed whereas a deeper vadose zone requires

the less expensive construction of fewer, but deeper wells.

Type of Soil

It is generally believed that sandy soils will take less time to remediate than clay soils. Whether the soil be sand or clay, sufficient air-filled porosity must exist in the soil matrix in order to effect a reasonable flow of extraction air.

Nature of the Contamination

The volatility and the Henry's Law Constant have a great effect on the time required to remediate a site. A material with a high value of Henry's Law Constant will take a shorter time to extract than will one with a low value. For the same air flow, the contaminant material with a higher Henry's Law Constant affords a higher partial pressure of this contaminant in the air stream than one with a lower Henry's Law Constant. This means more contaminant is removed per unit time. Remediation times for the materials with high and low Henry's Law Constants can be affected by employing different vacuum equipment, i.e., higher air flow and higher vacuum for the contaminant with the lower Henry's Law Constant.

Amount of Contamination

It is logical that a more-contaminated site will take longer to remediate. In addition, if offgas treatment is required (e.g., activated carbon), the higher carbon costs for the more contaminated site will increase the overall remediation cost.

Requirements for Offgas Treatment

Some sites will require only dispersion stacks for the offgas, depending on the toxicity of the contaminant. If offgas treatment is required (e.g., in the form of activated carbon), this can amount to as much as 30% of the cost/ton of the remediation. Large sites can have a system for regeneration of the activated carbon onsite, which can cut the cost of carbon almost in half.

Wastewater Generation Possibilities

If little or no water is recovered from the vadose zone, the costs/ton may be up to 20% lower than for a site with large amounts of water. If water is recovered it is usually cost-effective to run the collected groundwater through a carbon adsorption or air stripping unit prior to discharge on site, rather than disposal offsite. This would be significantly less expensive than the cost of offsite disposal of the wastewater.

Basis of Economic Analysis

The cost analysis was prepared by breaking the costs into twelve groups. These will be described in detail as they apply to the Terra Vac process. The categories, some of which do not have costs associated with them for this technology, are as follows:

- Site preparation costs -- including site design and layout, surveys and site investigations, legal searches, access rights and roads, preparations for support facilities, decontamination facilities, utility connections, and auxiliary buildings.
- Permitting and regulatory costs -- including permit(s), system monitoring requirements, and development of monitoring and analytical protocols and procedures.
- Equipment costs -- broken out by subsystems, including all major equipment items: process equipment, and residual handling equipment.
- Startup and fixed costs -- broken out by categories, including mobilization, shakedown, testing, depreciation, taxes, and initiation of environmental monitoring programs.
- Labor costs -- including supervisory and administrative staff, professional and technical staff, maintenance personnel, and clerical support.
- Supply costs -- includes raw materials.
- Supplies and consumables costs -- includes the utilities such as fuel and electricity.
- Effluent treatment costs -- includes offgas and wastewater treatment.
- Residual wastewater disposal costs -- including the preparation for shipping and the actual wastewater disposal charges.
- Analytical costs -- including laboratory analyses for operations and environmental monitoring.
- Facility modification, repair, and replacement costs -- including design adjustments, facility modifications, scheduled maintenance, working capital, and equipment replacement.
- Site demobilization costs -- including shutdown, mobile equipment decontamination and

demobilization, site cleanup and restoration, permanent storage costs, and site security.

Some general assumptions defining the basis of the estimates are as follows:

- A total of 6,000 yd^3 of soil are processed in the two cases estimated.
- Case 1 is based on the actual system operation costs for 56 days under the SITE program. Only partial remediation of 6,000 yd^3 of the Groveland Superfund site was achieved during the SITE demonstration. Case 2 is based on a complete remediation of a 6,000-yd^3 portion of the Groveland site. As discussed in Appendix C, the total remediation time is estimated to be 150 days.
- There is a prime contractor on site responsible for the complete site cleanup, who will provide certain functions for the Terra Vac unit (such as site preparation), whose costs are not included. These costs are expected to be site-specific, but minimal.

The twelve cost factors, along with the assumptions utilized, each are described below:

Site Preparation Costs

Site preparation consisted of the setup and outfitting of a trailer, which was used as a base of operations; the provision of electrical service for the trailer, the vacuum pump skid and water pump; the minor grubbing and cleaning of the site; and installation of extraction and monitoring wells. The vacuum pump skid required the extension of an existing 440-V, 3-phase, 60-Hz line in the Valley Manufactured Products plant back to the demonstration area, with the installation of a circuit breaker and electrical power meter. The trailer power line was run from a street pole and meter installed. Various outside lights and switches were installed to make the area more secure. During the drilling operations, the services of a health and safety officer were required to set forth the personnel protection requirements based on monitoring of VOC emissions. These costs are included as part of the site preparation costs.

Site preparation costs are highly site-dependent. Some sites may require the construction of access roads; however, no such expenses were incurred at the Groveland site.

Permitting and Regulatory Costs

Since Groveland is a Superfund site, it was assumed that no permits were required, either Federal nor State. The need for developing analytical protocols or monitoring records is assumed not to exist. On non-Superfund sites, this activity could be expensive and very time consuming.

Equipment Costs

Based on the information provided by Terra Vac, the capital cost of the equipment utilized at the Groveland site is estimated to be $50,000. This includes the costs for the design, engineering, materials and equipment procurement, and fabrication and installation of the Terra Vac's transportable unit. The cost of all subsystems and components installed on their respective skids and trailers is included; however, the cost of tractors for the transport of trailers is not included.

A contingency cost, approximately 10% of the equipment cost (per annum prorated to the actual time on site), is allowed for unforeseen costs. For Case 12, total use time of four months is assumed, whereas total use time of eight months is assumed for Case 2.

Startup and Fixed Costs

The costs included in this group are operating procedures and operator training, initial shakedown of the equipment, equipment depreciation, and insurance and taxes.

In order to ensure a safe, economical, and efficient operation of the unit, a program to train operators and operating procedures are necessary. The associated costs will accrue: the preparation of health-and-safety and operating manuals; the development and implementation of an operator training program; and equipment decontamination procedures. For this analysis, it was assumed that trained operators from Terra Vac were available, thus requiring no training costs. The costs shown in this category represent the costs to prepare the manual mentioned above.

Mobilization and shakedown costs include the transportation of the unit to the site, initial setup, onsite checkout, construction supervision, and working capital. Personnel travel costs to the site are not included. These costs are site-specific and may vary depending on the nature and location of the site.

The depreciation costs are based on a 10-yr life for all the equipment. Therefore, the costs are based on writing off $50,000 worth of equipment over ten years.

Insurance and taxes are lumped together and are assumed, for purposes of this estimate, as 10% of direct costs taken on an annual basis. Again, the effective duration of four months is assumed for Case 1, and eight months for Case 2.

Labor Costs

A major advantage of the Terra Vac technology is that it requires very few operating personnel, even at a very large remediation project. At the Groveland site, in the initial period, two operators were required, but once the system operation stabilized, only one was required, which was the case during the demonstration period. The main tasks for the operators were to take daily gas samples and replace carbon canisters. Assuming $25/h for the operator and one 8-h-shift/d coverage, the labor cost for 56 days of operation is $11,200. The living cost for the same period was estimated to be $5,400. In Case 2, in which the operation would last for 150 days to achieve full remediation, the living costs could be reduced a little by renting accommodations rather than using hotels. A 20% reduction from the prorated living expenses is assumed for Case 2.

Supply Costs

There are no supplies required in typical Terra Vac system operations.

Utility Costs

The only utility required for this technology is the electric power needed for the motors that operate the pumps, fans, vacuum pump, and the small separator water pump. Auxiliary electrical requirements to power the two field trailers and other site lighting are minimal and are included in the total utility costs. The cost of electricity used is $0.08/kWh.

Effluent Treatment

At the Groveland site, offgas from the vacuum extraction system was treated by the use of activated carbon. A total of 15,200 lbs of activated carbon was used during the 56 days of SITE demonstration. The cost of this activated carbon included the cost of regeneration.

The offgas treatment cost for Case 2 cannot be determined by prorating in the ratio of the total operating time. As the operation goes on, the amount of organics extracted by the system decrease exponentially. For this analysis, it was assumed that the cost of activated carbon required for full remediation would be approximately 50% higher than the cost during the demonstration. Since this extrapolation is based solely on engineering judgement, there is a significant uncertainty associated with it.

It must be emphasized that offgas treatment may not be required at all sites. For example, the remediation at the Upjohn Superfund site in Puerto Rico and the Bellview site in Florida required no offgas treatment.

Residual Disposal

At the Groveland site, 17,000 gal of wastewater was extracted during the demonstration. This contaminated water may be treated onsite or disposed of to a fully-permitted treatment facility. For the demonstration (Case 1), the wastewater was disposed of off site and the actual disposal costs are included in these costs. Again, it is assumed that for Case 2, the cost of wastewater disposal would be approximately 50% higher than the cost during the demonstration. It should be noted that there is a significant uncertainty associated with this cost for Case 2.

It is estimated that onsite treatment of the wastewater using a packed- column air stripper or activated carbon would reduce this cost by approximately 50%.

Again, this cost element is also very site-specific. At the Upjohn Superfund site, a separate groundwater treatment system was used since the contamination had also reached the aquifer. The small amount of contaminated water extracted from the vacuum extraction system was treated by the groundwater treatment system without any significant impact on the cost. At other sites, the system may not generate any wastewater at all.

Analytical Costs

These costs include the cost for pretest and posttest soil sampling and analyses, and the periodic sampling and analyses of wellhead gas and stack gas. The frequency of wellhead-gas and stack-gas analyses are site-dependent. Typically, Terra Vac sends one person to the site once a week with a portable gas chromatograph to perform these analyses. These costs for the SITE demonstration were much higher than estimated herein due to the nature of the testing. The costs included here are more representative of how a typical commercial operation would be remediated.

Facility Modification Costs

The costs accrued under this category include maintenance and working capital. Maintenance materials and labor costs are difficult to estimate and cannot be predicted as functions of preliminary design concepts. Therefore, annual maintenance costs are assumed to be 10% of capital costs. Working capital costs are assumed to be negligible, as all supplies purchased to have on hand are assumed to be fully consumed by the project's completion. The cost of using money early in the project is neglected.

Site Demobilization Costs

The only costs estimated for this category for the Groveland site were the decontamination and

demobilization costs. The cost of providing site security was not included. Since the site was not fully remediated, the costs associated with site restoration -- such as refilling and capping the wells, etc. -- was also not included.

Appendix A
Process Description

The vacuum extraction process is a technique for the removal of volatile organic compounds (VOCs) from the vadose (or unsaturated) zone of soils. This is the subsurface soil zone located between the surface soil and the groundwater. In general, VOCs are present in these soils in one of these ways: as dissolved constituents in the aqueous phase; as constituents adsorbed in the solid soil material; or as free constituents in the liquid and vapor phases in the void space of the soil. Once a contaminated area is completely defined, an extraction well or wells, depending on the extent of contamination, will be installed. The extraction well is connected by piping to a separator device.

Vacuum extraction wells are designed with a vacuum-tight seal near the surface and an extraction zone (screen) corresponding to the profile of subsurface contamination. Extraction systems may be vertical (wells) or horizontal (screens installed in trenches or horizontal borings). Horizontal systems are effective in areas where groundwater and contamination is very shallow (i.e., less than 10 ft) and removal of groundwater is to be minimized.

A vacuum pump or blower induces air flow through the soil, stripping and volatilizing the VOCs from the soil matrix into the air stream. Liquid water is generally extracted along with the contamination. Vacuum is applied to the vacuum extraction well via a manifold system. The vacuum at the wellhead is directly related to the radius of influence of the well and the cleanup rate that can be achieved; the higher the vacuum, the faster the cleanup. When vacuum is exerted on the well, subsurface vacuum propagates laterally, volatilizing contaminants in place. Subsurface air and vapors migrate toward the vacuum extraction well in response to the negative pressure gradient around the well.

The two-phase flow of contaminated air and water flows to a vapor/liquid separator where contaminated water is removed. The contaminated air stream then flows through activated carbon canisters arranged in parallel. Primary, or main, adsorbing canisters are followed by secondary, or backup, adsorbers to ensure that no contamination reaches the atmosphere. Table A-1 presents the required equipment for the site, Figure A-1 illustrates the layout of wells and equipment, and Figure A-2 shows a schematic diagram of an extraction well.

In order for a vacuum extraction system to be successful, the system design would have to consider a number of important variable parameters. These parameters are listed in Table A-2. The control variables are the parameter that one has control over in the design and operation of the vacuum extraction system. The response variables are the parameters that change in response to change in the control variables. The initial variables are the parameters that exist initially at the site. The spacing of vacuum extraction wells is critical to efficient remediation. Depending on the depth to groundwater and the soil type, the radius of influence of an extraction well can range from tens to hundreds of feet. Soil permeability, porosity, moisture content, stratigraphy, and depth of groundwater are important factors in determining the radius of influence. Terra Vac's vapor flow models are often calibrated to site conditions to determine design parameters and sensitivity before pilot testing or full-scale cleanup is implemented.

Site conditions, soil properties, and the contaminant chemical properties are the important considerations in determining the success of a vacuum extraction system. The depth of the vadose zone should be at least 10 feet for cost effectiveness, since beyond this depth excavation costs become very expensive and far outstrip the costs of installing a vacuum extraction system. The soil should have a sufficient air-filled porosity to allow the vacuum and the extraction air to do its job of in situ stripping of the VOCs from the soil matrix. Water is a deterrent to this stripping action as the water reduces the air-filled porosity. The contaminant should have a Henry's Constant of 0.001 or more for it to be removed effectively in a vacuum extraction system. Table A-3 lists the Henry's Constant at a temperature of 10°C for typical VOCs. The compounds are easier to remove by the vacuum extraction process as one goes down the list.

Table A-1. Groveland Site Equipment List

Equipment	Number required	Description
Extraction wells0.	4 (2 sections each)	2 in. Sched. 40 PVC, 24-ft total depth
Monitoring wells	4 (2 sections each)	2 in. Sched. 40 PVC, 24-ft total depth
Vapor-liquid separator	1	1,000-gal capacity, steel
Activated carbon canisters	Primary: 2 units in parallel	Canisters with 1,200 lb of carbon in each canister - 304 SS
	Secondary: 1 unit	4 in. inlet and outlet nozzles
Vacuum pump skid	1	Terra Vac recovery unit model 17 25 HP motor
Holding tank	1	2,000-gal capacity, steel

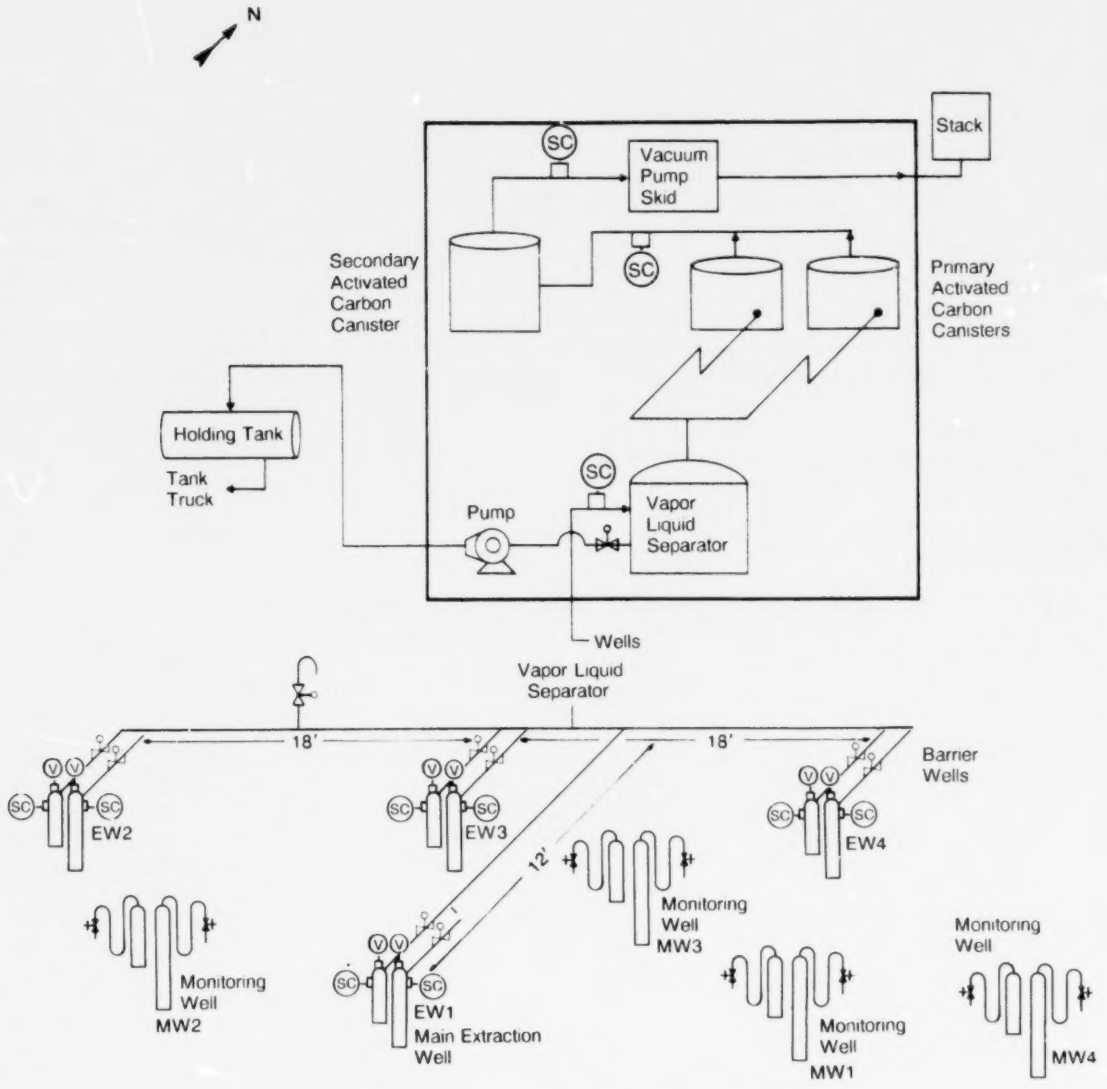

Figure A-1. Schematic diagram of equipment layout.

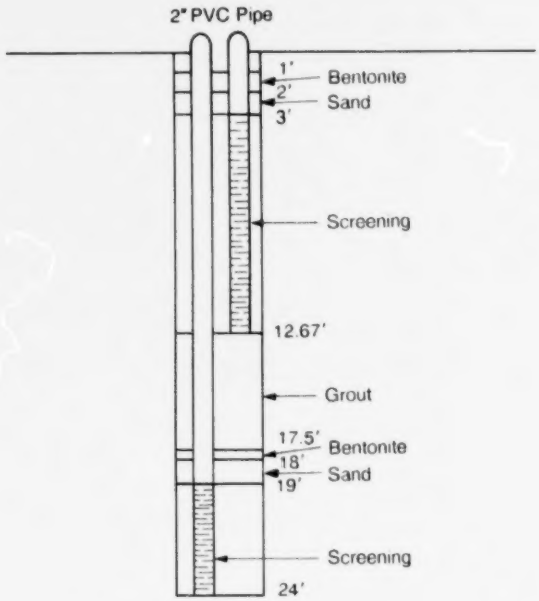

Figure A-2. Schematic diagram of an extraction well.

Table A-2. System Variables

Variables	Control	Response	Initial
1. Initial soil VOCs			X
2. Final soil VOCs		X	
3. Extracted air VOCs		X	
4. Depth to groundwater			X
5. Soil permeability			X
6. Soil moisture			X
7. Soil porosity			X
8. Soil bulk density			X
9. Soil particle density			X
10. Soil organic carbon			X
11. Henry's Constant			X
12. Solubility			X
13. Adsorption equilibria			
14. Temperature		X	X
15. Well-head vacuum	X		
16. Extracted air flow	X		
17. Extraction well spacing	X		
18. Screened depth	X		
19. Duration of operation	X		
20. Radius of influence		X	
21. Power consumption		X	

Table A-3. Dimensionless Henry's Law Constants for Typical VOCs @ 10°C

1.	methyl ethyl ketone	0.0121
2.	ethylene dibromide	0.0129
3.	1,1,2,2-tetrachloroethane	0.0142
4.	dibromochloromethane	0.0164
5.	1,1,2-trichloroethane	0.0168
6.	methyl isobutyl ketone	0.0284
7.	tetralin	0.0323
8.	1,2-dichloroethane	0.0504
9.	1,2-dichloropropane	0.0525
10.	1,2,4-trichlorobenzene	0.0555
11.	methylene chloride	0.0603
12.	1,2-dichlorobenzene	0.0702
13.	chloroform	0.0740
14.	1,4-dichlorobenzene	0.0702
15.	1,3-dichlorobenzene	0.0951
16.	chlorobenzene	0.1050
17.	cis-1,2-dichloroethylene	0.1162
18.	o-xylene	0.1227
19.	ethylbenzene	0.1403
20.	benzene	0.1420
21.	methyl ethyl benzene	0.1511
22.	1,1-dichloroethane	0.1584
23.	toluene	0.1640
24.	1,3,5-trimethylbenzene	0.1734
25.	m-xylene	0.1769
26.	p-xylene	0.1808
27.	trichloroethylene	0.2315
28.	propylbenzene	0.2445
29.	trans-1,2-dichloroethylene	0.2539
30.	chloroethane	0.3267
31.	2,4-dimethylphenol	0.3568
32.	tetrachloroethylene	0.3641
33.	1,1,1-trichloroethane	0.4153
34.	carbon tetrachloride	0.6370
35.	vinyl chloride	0.6456
36.	1,1-dichloroethylene	0.6628
37.	methyl cellosolve	1.8980
38.	trichlorofluoromethane	2.3068
39.	decalin	3.0127
40.	cyclohexane	4.4329
41.	1,1,2-trichlorotrifluoroethane	6.6279
42.	n-hexane	10.2430
43.	nonane	17.2152
44.	2-methylpentane	29.9975

Appendix B
Vendor's Claims for the Technology

(NOTE: The following material was provided by Terra Vac directly.)

Introduction

Vacuum extraction technology effectively removes volatile and semivolatile compounds from soils and groundwater. Removal of liquid-phase hydrocarbons floating on the water table using vacuum extraction technology is faster and more effective than traditional approaches. Vacuum extraction is typically implemented in situ; however, treatment of excavated soils onsite using vacuum extraction technology is also effective. Groundwater can be removed simultaneously from vacuum extraction wells to further enhance recovery of groundwater contaminants and reduce the time frame for total cleanup.

Vacuum extraction technology was originally developed by Terra Vac. Since its inception more than five years ago, the technology has been widely used to clean up soil and groundwater contaminated with volatile organic compounds (VOC). Two broadly applicable process patents exist that relate directly to vacuum extraction and the process of removing volatile contaminants from the vadose zone using vacuum (US Patent Nos. 4,593,760 and 4,660,639). Most applications of the technology require a license to use vacuum extraction to remove VOCs from the vadose zone.

Cleanup of contaminated soils is often the most important aspect of rapid, cost-effective remediation at sites contaminated with volatile organics. A leaky tank or pipeline, surface spill, storage lagoon, landfill, or other release can quickly contaminate a large volume of subsurface soil and rock. Vacuum extraction removes contaminants directly from the source area, eliminating further migration. Implementation can be immediate, without risk of complicating future cleanup efforts.

The high incidence of soil contamination observed at leaky underground storage systems, industrial sites, and Superfund sites requires that efficient and cost-effective solutions be found to achieve cleanup activities. Industrial experience with groundwater remediation has shown that where soils are contaminated and allowed to remain in place untreated, the groundwater cleanup process is costly and lengthy. Furthermore, without effective source control, remedial efforts may never restore the groundwater for use as a potable supply.

Potential Application

Waste Compatible with Technology

Vacuum extraction technology is effective in treating soils containing virtually any chemical with a volatile character. All of the volatile priority pollutants and many of the semivolatiles have been successfully extracted with the vacuum process. However, metals (except mercury), heavy oils, and PCBs will remain in place as the volatile compounds are extracted by the process.

Terra Vac has applied vacuum extraction at more than 60 sites across the country. Applications range from small gas stations to large Superfund sites. Large volumes (up to 7 million yd^3) of contaminated soil have been treated effectively with the process. Remediation is rapid due to the high recovery rates that have been achieved by Terra Vac: up to 4,000 lb/d from a single well.

Contaminants Removed--

Terra Vac has successfully extracted the following chemicals:

Volatiles:

benzene
toluene
xylenes
ethylbenzene
hexane
chloroform
methylene chloride
tetrachloroethylene (PCE)
trichloroethylene (TCE)
dichloroethylene (DCE)
ethyl acetate
cyclohexane
methyl ethyl ketone (MEK)
methyl isobutyl ketone (MIBK)

methanol
acetone
pyridine
tetrahydrofuran
dimethylfuran
carbon tetrachloride
trichloroethane (TCE)

Semivolatiles:

chlorobenzene
dichlorobenzene (DCB)
trichloropropane

Hydrocarbons:

gasoline
jet fuel
Stoddard solvent
diesel
kerosene
heavy naphthas

For those sites with numerous types of compounds (i.e., VOCs, PCBs, pesticides, and metals) a phased approach is often required. In these cases, it is prudent to remove VOCs *first* using vacuum extraction so that other technologies can then be applied more cost-effectively and safely. For example, in the chemical treatment or incineration of soil, which requires excavation, the health risk of excavation is minimized if the majority of VOCs are removed first, in situ, by vacuum extraction. Not only is the health risk minimized but also the excavation is accomplished faster and more economically because of the lower level of protection required. Many methods used to chemically stabilize metals are more effective after vacuum extraction has removed VOCs.

Concentration Limits--
Vacuum extraction of VOCs has been applied at numerous sites by Terra Vac to reduce soil and groundwater contaminant levels from saturated conditions down to nondetectable. Therefore, concentration limitations are virtually eliminated with this technology. Dual vacuum extraction of groundwater and vapors has been effective at restoring groundwater quality to drinking water standards within short periods of time.

Favorable Conditions for Vacuum Extraction Technology

Vacuum extraction has been demonstrated by Terra Vac to be effective in virtually all hydrogeologic settings:

- clays
- silts
- sands and gravel
- alluvium, colluvium, and glacial till
- wetlands
- fractured rock and karst

Advantages of vacuum extraction systems are that cleanup of contaminated soil, free product, and groundwater is in situ, rapid, and low cost. (See Table B-1 for a breakdown of costs for remediation estimated for the Groveland site.) Vacuum extraction systems are not limited by depth to groundwater, with successful application demonstrated by Terra Vac at sites with groundwater as deep as 300 ft and as shallow as 3 in.

Table B-1. Terra Vac's Estimated Cost for Complete Remediation of Valley Property at Groveland, $/Ton

Site preparation and design	0.70
Permitting and regulatory	--
Equipment:	
Rental	4.20
Consumables (piping and materials)	0.40
Contingency (10% of direct costs)	2.67
Startup and fixed cost	
Installation	2.50
Startup	0.60
Mobilization and shakedown	0.30
Depreciation (10% of direct costs)	2.67
Insurance and taxes (10% of direct costs)	2.67
Labor costs	5.82
Supplies - Raw materials	5.82
Supplies - Utilities	
Electricity	3.30
Effluent treatment, liquid and vapor	6.00
Residual disposal (included in effluent treatment)	--
Analytical	3.90
Facility modifications (10% of direct costs)	2.67
Site demobilization	0.20
TOTAL	38.60

Pumping and treating groundwater is usually conducted at all sites where groundwater quality is significantly impacted. However, pump and treat systems alone do not treat the soils and source areas directly. Initial capital costs may be low to moderate, but high operations and maintenance costs are required as contaminants continue to leach from and to soils. Pumping and treating groundwater alone is

very slow, taking decades to restore aquifers to common cleanup goals.

Free Product Removal--
Vacuum extraction is an effective means of removing hydrocarbons floating on the water table. Compared to typical double-pump systems, skimmer pumps, or air-displacement product-recovery systems, vacuum extraction is faster, more effective, and low in cost per gallon of product removed. Liquid-phase hydrocarbons are removed without pumping groundwater so that separation and treatment of large volumes of contaminated water is eliminated.

Where free product is present, traditional pump-and-treat systems can cause groundwater quality to become worse. As residual hydrocarbons are spread throughout the cone of depression of a pumping well, groundwater concentrations rise significantly whenever pumps are turned off. However, if combined with vacuum extraction, complete remediation of soils and groundwater can be achieved.

Dual Extraction--
Where contaminants have already reached the groundwater, a "dual extraction" approach is effective. Dual extraction is a term used to describe the process of simultaneously extracting groundwater and vapors under vacuum, using the same well. In the simplest form, operating a submersible pump within a vacuum extraction well will lower the water table and increase the effective unsaturated zone in which the vacuum extraction process will vaporize contaminants.

Simultaneous extraction of groundwater and vapors under vacuum has several benefits that enhance the rate of groundwater cleanup. First, the rate of contaminant removal increases compared to groundwater extraction alone since contaminants have two pathways for removal -- aqueous phase and vapor. Even in areas were there have been no sources of soil contamination other than that provided by groundwater movement beneath the water table, the dual extraction process often yields the same mass flux (i.e., lb/d) from the vapor phase as the aqueous phase. In medium-to-low permeability aquifers the maximum rate at which groundwater can be extracted from a given well increases two-to-three fold. The net effect of these two phenomena can yield a 6-fold increase in the overall contaminant removal rate, and hence, a 6-fold reduction in the time required to reach cleanup objectives.

Case Studies

The Terra Vac system was first demonstrated at a Superfund site in Puerto Rico -- the Upjohn facility in Barceloneta -- where carbon tetrachloride leaked from an underground storage tank. The first aquifer was the sole source of drinking water 300 feet below. Although groundwater contamination occurred rapidly, most of the pollutant was in the soil. Terra Vac has remediated its assigned portion of this Superfund site.

Since the first application in Puerto Rico, Terra Vac has applied the vacuum extraction process to more than 40 sites across the country. The process for the removal of volatile contaminants from the vadose zone of contaminated ground using vacuum extraction is patented (U.S. Patent Nos. 4593760 and 4660639).

Following is a list of Terra Vac projects that are either completed or are in various stages of completion (see Table B-2):

1. Superfund Site, Puerto Rico

   The cleanup of a large area contaminated with carbon tetrachloride resulted in the development of Terra Vac's vacuum extraction process. The first three months of the project demanded daily interaction with EPA officials, local agencies, and regulators, since several municipal wells were impacted. The vacuum extraction process was developed in stages to recover solvents from depths up to 300 ft, over an area of nearly 600,000 ft^2. The process recovered up to 800 lb/d of carbon tetrachloride. As a result of Terra Vac's process, more than 80% of the spill volume has been recovered, and groundwater concentrations have been reduced by 95%-99%.

2. Superfund Site, California

   Terra Vac designed, built, and operated a series of vacuum extraction pilot tests for the recovery of a wide range of solvents (including DCE, TCE, and DCB) from clayey subsoil beneath an active microchip manufacturing facility. Operation of the extraction system required close monitoring, due to the political climate in the area and the close proximity of several resident communities. The activated-carbon treatment system was designed and operated for compliance with Bay Area Air Quality standards while still maintaining high carbon-usage efficiencies.

3. Verona Well Field Superfund Site, Michigan

   The Verona Well Field was the first Superfund site where EPA specified in the ROD that vacuum extraction be used to clean up the subsoils. Terra Vac was awarded the contract based on its technical proposals and costs. The pilot test for this site has been completed and the full-scale vacuum-extraction-system (VES) is

Table B-2. Partial List of Terra Vac Projects

Site	Type	Date Start/End	Compounds	Depth to Groundwater (ft)	Soil Type	Length of Operation	Cleanup Goal	Initial Recovery Rate (lb/d)	Status
Tyson's	Superfund	Nov 86/May 87	TCP, PCE TCE Xylenes Toluene Benzene	18	Clay	30 days	Pilot Test	20-100	Full-scale system under construction
Barceloneta Spill	Superfund	Nov 82/Nov 86	CCL_4	300	1. Clay 2. Rock	2.5 years	No	250	Achieved goals
Verona Michigan	Superfund	Sep 87/On going	PCE, TCE MEK MIBK BTEX	25	Sand/Silt	1 month	1 ppm	2,000	On going cleanup
South Carolina	Industrial	Oct 86/On Going	PCE	12-20	Clay	1 year	No	100	On going 90% cleanup
Michigan	Industrial	Dec 86/Oct 87	TCE PCE	35	Sand	3 months	Drinking water	30-80	Achieved goals
Puerto Rico	Major Oil Refinery	Jul 85/Aug 86	Gasoline Benzene	11	Sand/Silt	1 year	5 ppb benzene	2,000	Goal achieved
Puerto Rico	Gas station	June 85/Aug 85	Benzene Toluene Xylenes Combustibles	2-11	Clay/Silt	2 months	No	300	Goal achieved
Belleview Florida	Gas station	Jan 86/Aug 87	Benzene Toluene Xylene Gasoline	50	Clay/Sand Rock	4 months	Demonstrate technology	2,000	Demonstration completed
Manati Puerto Rico	Industrial underground tanks	Dec 84/Feb 85	Hexane DMF THF Acetone	13	Sand	3 months	1 gal/day extraction rate	400	Cleanup complete on going monitoring
Sites Demo Massachusetts	Superfund	Dec 87/Apr 88	TCE	25	Sand/Clay	50 days	Demonstrate technology	60	Demonstration completed

being designed and installed. The project is expected to last two years.

4. Tyson's Superfund Site, Pennsylvania

   A pilot vacuum extraction system (VES) was installed to remove residual hydrocarbons and solvents from old disposal areas. The system used activated carbon to eliminate discharge of hazardous components. The recovery rates from the system totalled 150 lb/d of benzene, toluene, xylenes, TCE, PCE, and trichloropropane. Based upon the pilot test results, EPA has modified the previous ROD to specify vacuum extraction as the preferred remedial technology. Terra Vac worked with the client and the client's consultant on the design of a VES to clean the entire site. Terra Vac was responsible for successful cleanup of the site. Total estimated cost of the cleanup was $4M.

5. Industrial Client, New Jersey

   The site of a former chemicals-manufacturing facility contained abandoned lagoons contaminated with volatile organics. Terra Vac has designed a pilot test in this hydrogeologically complex setting that will use a dual extraction system to recover contaminants deep within clayey sediments. The initial groundwater level was within six in. of the surface. The pilot test is underway to determine whether vacuum extraction can be used to successfully remove volatile organics from subsoils at the site.

6. EPA, Massachusetts

   Terra Vac was selected by EPA to demonstrate vacuum extraction for the Superfund Innovative Technology Evaluation (SITE) Program. The purpose of the program is to document the effectiveness of proven technologies.

7. Industrial Client, New Hampshire

   Terra Vac is performing a pilot test of the vacuum extraction process at this Superfund Site for the Potentially Responsible Party (PRP) Committee. The pilot test will demonstrate the efficacy of the Terra Vac extraction process as part of the Feasibility Study. The site contains various chlorinated and aromatic solvents.

8. Industrial Client, Wisconsin

   Terra Vac completed a cleanup of approximately 250 gal of high-boiling-point heavy-naphthas from a former tank location. The cleanup was accomplished in one month.

9. State Environmental Agency, Florida

   Terra Vac conducted a pilot test for the recovery of gasoline from an underground pipeline leak at a service station. The pilot test was successful and continued for full cleanup of the site. The cleanup achieved soil concentrations below the proposed Florida Dept. of Environmental Regulations (DER) limits for the indicator compounds (including benzene) at 1 ppb.

10. Industrial Client, Michigan

    Terra Vac installed a pilot VES to recover TCE and PCE in soils that were contaminated from old housekeeping problems. The pilot test was extended into a full cleanup operation. The cleanup goal of 5 ppb was achieved by early 1988.

11. Department of Energy, South Carolina

    Terra Vac performed a pilot test of soil contaminated with solvent from a leaking pipeline. Successfully removed more than 250 lb/d of PCE and TCE from highly stratified sediments to a depth of 120 ft. Further testing will follow to determine design parameters for a full-scale cleanup.

12. Industrial Client, North Carolina

    Vacuum extraction is being used to remove PCE and TCE from soil and lagoon sludge. Recovery rates of 100 to 300 lb/d have been achieved. Also, Terra Vac successfully recovered solvents from under a building where sump leaks had occurred. Full cleanup is expected by mid-1988.

13. Petroleum Spill, Puerto Rico

    Efforts by conventional methods to remove floating hydrocarbons from perched groundwater after a pipeline leak were futile. Terra Vac installed a vacuum recovery process that removed residual hydrocarbons and about 1 in. of free product within ten days of operation. Floating product was perched above clayey soils in gravel backfill. All traces of free product were eliminated from monitoring wells.

14. Petroleum Client, Puerto Rico

    A leaky tank caused gasoline to seep into surrounding soils. The contaminated soil provided a source of hydrocarbon vapors to a nearby underground utility line. During installation of the electrical cables, explosive conditions in the underground line interrupted operations immediately. Up to 7 in. of free

product was observed in the vacuum extraction wells installed at the site.

15. Industrial Client, Puerto Rico

    The soil around eight underground tanks is being monitored for hydrocarbons by using the Terra Vac vacuum extraction process. Monthly testing for leaks has successfully detected several leaks and spills. The same vacuum system is being used for cleanup of the site.

16. Petroleum Client, Puerto Rico

    A tank leak at a service station caused gasoline contamination of a sewer and creek outfall. Terra Vac operated a three-phase recovery system for vapors, free product, and contaminated groundwater. Complete cleanup of the area took place in 14 weeks.

17. Petroleum Client, Puerto Rico

    A leak at a service station reportedly released 800 gal of gasoline. After 13 weeks of vacuum extraction, Terra Vac had reduced hydrocarbon levels in soils from 600 ppm to nondetectable. The equivalent of more than 1,400 gal of gasoline were recovered.

Cost Effectiveness

Vacuum extraction is typically more cost-effective than any other treatment technology for soils contaminated with VOCs. Typical implementation costs range from $\$10/yd^3$ to $\$50/yd^3$. For extraction of liquid-phase hydrocarbons floating on the water table, vacuum extraction costs about \$10/gal of gasoline to \$35/gal for complete onsite destruction of hydrocarbons and compliance with rigorous air-emissions controls. This compares to about \$50/gal for product recovery using typical dual-pump, total-fluids or skimmer-type systems.

Appendix C
Site Demonstration Results

Introduction

This SITE program demonstration test was planned to determine the effectiveness of Terra Vac Inc.'s vacuum extraction technology in the removal of volatile organic compounds from the vadose zone. The location of the test was on the property of an operating machine shop. The property is part of a Superfund site and is contaminated by degreasing solvents, mainly trichloroethylene.

Objectives

The main objectives of this project were:

- The quantification of the contaminants removed by the process.
- The correlation of the recovery rate of contaminants with time.
- The prediction of operating time required before achieving site remediation.
- The effectiveness of the process in removing contamination from different soil strata.

Approach

The objectives of the project were achieved by following a Demonstration Test Plan, which included a Sampling and Analytical Plan. The Sampling and Analytical Plan contained a Quality Assurance Project Plan (QAPP). This QAPP assured that the data collected during the course of this project would be of adequate quality to support the objectives.

The sampling and analytical program for the test consisted of four periods: pretest (or pretreatment); active; midtreatment; and posttreatment.

The pretreatment sampling program consisted of:

- soil boring samples taken with split spoons
- soil boring samples taken with Shelby tubes
- soil gas samples taken with punch bar probes

Soil borings taken by split spoon sampling were analyzed for volatile organic compounds (VOCs) using headspace screening techniques, purge and trap, GC/MS procedures, and the EPA-TCLP procedure. Additional properties of the soil were determined by sampling using a Shelby tube, which was pressed hydraulically into the soil by a drill rig to a total depth of 24 ft. These Shelby tube samples were analyzed to determine physical characteristics of the subsurface stratigraphy such as bulk density, particle density, porosity, pH, grain size, and moisture. These parameters were used to define the basic soil characteristics.

Shallow soil-gas concentrations were collected during pre-, mid-, and posttreatment activities. Four shallow vacuum-monitoring-wells and twelve shallow punch-bar-tubes were used at sample locations. The punch bar samples were collected from hollow stainless steel probes that had been driven to a depth of 3 to 5 ft. Soil gas was drawn up the punch bar probes with a low-volume personal pump and tygon tubing. Gas-tight 50-mL syringes were used to collect the sample out of the tygon tubing.

The active treatment period consisted of collecting samples of:

- wellhead gas
- separator outlet gas
- primary carbon outlet gas
- secondary carbon outlet gas
- separator drain water

All samples with the exception of the separator drain water were analyzed on site. Onsite gas analysis consisted of gas chromatography with a flame ionization detector (FID) or an electron capture detector (ECD). The FID was used generally to quantify the trichloroethylene (TCE) and trans 1,2-dichloroethylene (DCE) values, while the ECD was used to quantify the 1,1,1-trichloroethane (TRI) and the tetrachloroethylene (PCE) values. The use of two detectors, FID and ECD, was necessitated by high

concentrations of TCE in the extracted wellhead gas. Owing to the high TCE concentrations, most of the samples injected on the ECD had to be diluted. Even with dilution factors of 333 to 1, the TCE concentration on the ECD would exceed the linear range of the detector, thus necessitating the use of two detectors.

The separator drain water was analyzed for VOC content using SW846 8010. Moisture content of the separator inlet gas from the wells was analyzed using EPA Modified Method 4. This method is good for the two-phase flow regime that existed in the gas emanating from the wellhead. Table C-1 lists analytical methods used for this project.

Table C-1. Analytical Methods

Parameter	Analytical method	Sample source
Grain size	ASTM D422-63	Soil borings
pH	SW846* 9040	Soil borings
Moisture (110°C)	ASTM D2216-80	Soil borings
Particle density	ASTM D698-78	Soil borings
Oil and grease	SW846* 9071	Soil borings
EPA-TCLP	F.R. 11/7/86, Vol. 51, No. 216, SW846* 8240	Soil borings
TOC	SW846* 9060	Soil borings
Headspace VOC	SW846* 3810	Soil borings
VOC	GC/FID or ECD	Soil gas
VOC	GC/FID or ECD	Process gas
VOC	SW846* 8010	Separator liquid
VOC	SW846* 8010	Groundwater
VOC	Modified P&CAM 127	Activated carbon
VOC	SW846* 8240	Soil borings

*Test Methods for Evaluating Solid Waste, 3rd Ed., Nov. 1986.

The posttreatment sampling essentially consisted of repeating pretreatment sampling procedures at locations as close as possible to the pretreatment sampling locations.

The activated carbon canisters were sampled, as close to the center of the canister as possible, and these samples were analyzed for VOC content as a check on the material balance for the process. The method used was P&CAM 127, which consisted of desorption of the carbon with CS_2 and subsequent gas chromatographic analysis.

Results

VOC Removal from the Vadose Zone

The permeable vadose zone at the Groveland site is divided into two layers by a horizontal clay lens, which is relatively impermeable. Each extraction well had separate shallow and deep sections to enable VOCs to be extracted from sections of the vadose zone above and below the clay lens. The quantification of VOCs removed was achieved by measuring:

- gas volumetric flow rate by rotameter, and wellhead gas VOC concentration by gas chromatography
- the amount of VOCs adsorbed by the activated carbon canisters by desorption into CS_2 followed by gas chromatography.

VOC flow rates were measured and tabulated for each well section separately. The results of gas sampling by syringe and gas chromatographic analysis indicate a total of 1,297 lb of VOCs were extracted over a 56-day period, 95% of which was TCE. A very good check on this total was made by the activated-carbon VOC analysis, the results of which indicated a VOC recovery of 1,353 lb; virtually the same result was obtained by these two very different methods.

One view of the reduction in VOC concentrations in the vadose zone can be seen from examining the three-dimensional shallow soil-gas plots. Soil gas was collected during pretreatment, midtreatment, and posttreatment from punch bar probes and shallow vacuum monitoring-wells. The collection points were located on a coordinate system with Extraction Well 1 as the origin (0,0).

Each collection point has an x and y coordinate, and TCE concentrations are plotted on a "Z" scale, which gives a three-dimensional plot across the grid. Values of "Z" between data points and around the grid are generated by the Kriging technique, which uses given data points and a regional variable theory to generate values between and around sample locations. Kriging is the name given to the least squares prediction of spatial processes and is used in surface fitting, trend surface analysis, and contouring of sparse spatial data.

A total of 12 shallow punch-bar-tubes were used, along with the 4 shallow vacuum monitoring-wells. The punch bars were driven to a depth of 3 to 5 ft, and, as with the vacuum wells, soil gas was drawn up the punch bar probes with a low-volume personal pump and tygon tubing. Gas-tight syringes (50 mL) were used to collect the sample out of the tygon tubing. The gas samples were analyzed in the field trailer using gas chromatographs with flame ionization detectors and electron capture detectors.

The soil gas results show a considerable reduction in concentration over the course of the 56-day demonstration period, as can be seen from Figures C-

1 and C-2. This is to be expected, since soil gas is the vapor halo existing around the contamination and should be relatively easy to remove by vacuum methods.

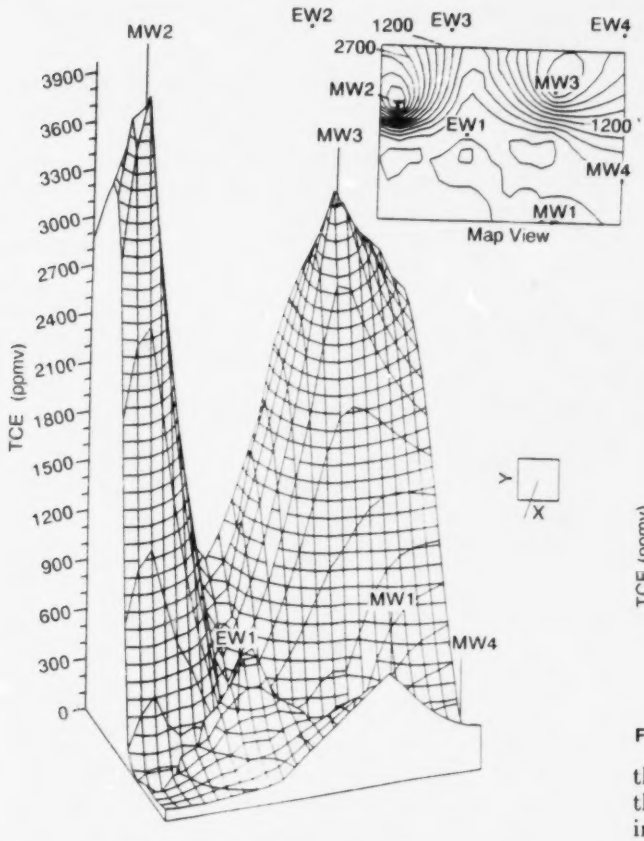

Figure C-1. Pretreatment shallow soil-gas concentration.

A more modest reduction can be seen in the results obtained for soil VOC concentrations by GC/MS purge-and-trap analytical techniques. Soil concentrations include not only levels seen in the vapor halo, but also interstitial liquid contamination that is either dissolved in the moisture in the soil or that exists with the moisture as a two-phase liquid.

Table C-2 shows the reduction of the weighted-average TCE levels in the soil during the course of the 56-day demonstration test. The weighted-average TCE level was obtained by averaging soil concentrations obtained every two feet by split-spoon sampling methods over the entire 24-ft depth of the wells. The largest reduction in soil TCE concentration occurred in EW4, which had the highest initial level of contamination. EW1, which was expected to achieve the greatest concentration reduction, exhibited only a minor decrease over the course of the test. Undoubtedly this was because of

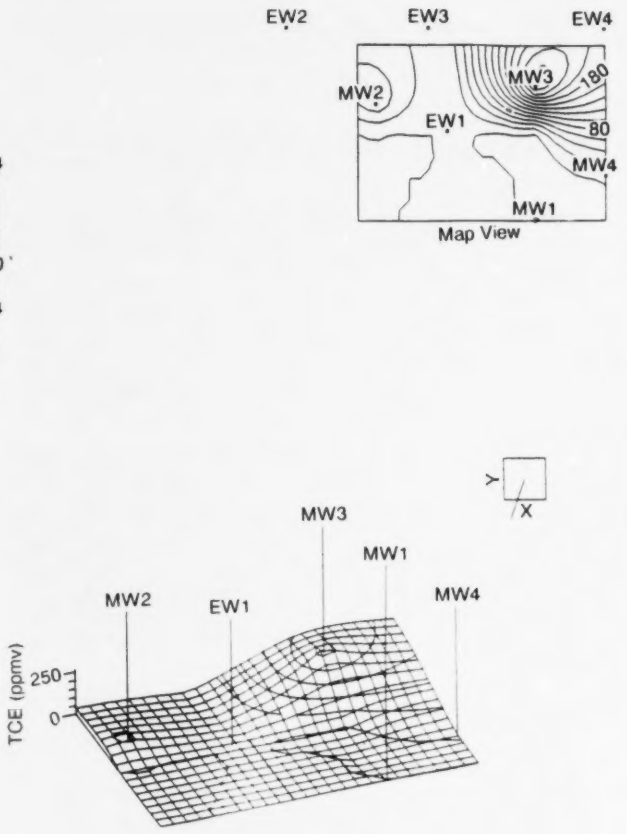

Figure C-2. Posttreatment shallow soil-gas concentration.

the greater-than-expected level of contamination that existed in the area around MW3 that was drawn into the soil around EW1. The decrease in the TCE level around MW3 tends to bear this out.

Table C-2. Reduction of Weighted Average TCE Levels in Soil (TCE concentration in mg/kg)

Well	Pretreatment	Posttreatment	% Reduction
EW1	33.98	29.31	13.74
EW2	3.38	2.36	30.18
EW3	6.89	6.30	8.56
EW4	96.10	4.19	95.64
MW1	1.10	0.34	69.09
MW2	14.75	8.98	39.12
MW3	227.31	84.50	62.83
MW4	0.87	1.05	-

Extraction wells 2, 3, and 4 were designed to be barrier wells for EW1. This means that they were designed to intercept contamination from the highest contaminated soils, which were under the building. Since the area around MW3 was highly contaminated and well within the radius of influence

of EW1, the extraction wells EW1, EW2, and EW3 in effect became barrier wells for EW4. The soil adjacent to EW4 thus was cleaned to a far greater extent that the other three wells.

Effectiveness of the Technology in Various Soil Types

The soil strata at the Groveland site can be characterized generally as consisting of the following types in order of increasing depth:

- medium to very-fine silty sands
- stiff and wet clays
- sand and gravel

Soil porosity, which is the percentage of total soil volume occupied by pores, was relatively the same for both the clays and the sands. Typically, porosity over the 24-ft depth of the wells would range between 40% and 50%. Permeabilities, or more accurately hydraulic conductivities, ranged from 10^{-4} cm/s for the sands to 10^{-8} cm/s for the clays, with corresponding grain sizes in the range to 10^{-1} to 10^{-3} mm.

Pretest soil boring analyses indicated in general that most of the contamination was in the stratum above the clay lens, with a considerable quantity perched on top of the clay lens. This was the case for EW4, which showed an excellent reduction of TCE concentration in the medium-to-fine sandy soils existing above the clay layer, with no TCE detected in the clay in either the pretest or posttest borings (see Table C-3). One of the wells, however, was an exception. This was MW3, which contained the highest contamination levels of any of the wells, and was exceptional in that most of the contamination was in a wet clay stratum (see Table C-4). The levels of contamination were in the 200-1,600 ppm range before the test. After the test, analyses of the soil boring adjacent to MW3 showed levels in the range of ND-60 ppm in the same clay stratum. The data, as shown in Table C-5, suggest that the technology can desorb or otherwise mobilize VOCs out of certain clays.

From the results of this demonstration, it appears that the permeability of a soil need not be a consideration in applying the vacuum extraction technology. This may be explained by the fact that the porosities were approximately the same for all soil strata, so that the total flow area for stripping air was the same in all soil strata. It will take a long time for a liquid contaminant to percolate and permeate through clay with its small pore size and consequent low permeability. However, the much smaller air molecules of vapor contaminant have a lower resistance in passing through the same pores.This may explain why contamination was generally not present in the clay strata, but when it was, it was not difficult to remove. Further testing should be done in order to confirm this finding.

Correlation of Declining VOC Recovery Rates to Time

The vacuum extraction of volatile organic constituents from the soil may be viewed as an unsteady state process taking place in a nonhomogeneous environment acted upon by the combined convective forces of induced stripping air and by the diffusion of volatiles from a dissolved or sorbed state. As such it is a very complicated process, even though the equipment required is very simple.

Unsteady-state diffusion processes in general correlate well with time by plotting the logarithm of the rate of diffusion versus time. Although the representation of the vacuum extraction process presented here might be somewhat simplistic, the correlation obtained by plotting the logarithm of the concentration of contaminant in the wellhead gas versus time and obtaining a least-squares best-fit line was reasonably good. This type of plot, shown in Figure C-3, represents the data very well and is more valid than both a linear graph or one plotting concentration versus log time, in which a best fit curve would actually predict gas concentrations of zero or less.

Looking at the plots for EW1, shallow and deep, equations are given for the least-squares best-fit line for the data points. If the vacuum extraction process is run long enough so that the detection limit for TCE on the ECD, which is 1 ppbv, is reached, the length of time required to reach that concentration would be approximately 250 days on the shallow well and approximately 300 days on the deep well.

Prediction of Time Required for Site Remediation

The soil concentration that would be calculated from the wellhead gas concentration using Henry's Law is included in the last column of Table C-5. Calculations for the predicted soil concentrations were made assuming a bulk density of the soil of 1,761 kg/m^3, a total porosity of 50%, and a moisture content of 20%. The calculated air-filled porosity of the soil is approximately 15%. Henry's Constant was taken to be 0.492 kPa/m^3-gmol at 40°F

Given the nonhomogeneous nature of the subsurface contamination and interactions of TCE with organic matter in the soil, it was not possible to obtain a good correlation between VOC concentrations in wellhead gas and soil in order to predict site remediation times. Henry's Law Constants were used to calculate soil concentrations from wellhead gas concentrations; and the calculated values obtained,

Table C-3. Extraction Well 4: TCE Reduction in Soil Strata

Depth (ft)	Description of strata	Permeability (cm/s)	TCE conc., ppm	
			pre	post
0-2	Med. sand w/gravel	10^{-4}	2.94	ND
2-4	Lt. brown fine sand	10^{-4}	29.90	ND
4-6	Med. stiff lt. brown fine sand	10^{-5}	260.0	39.0
6-8	Soft dk. brown fine sand	10^{-5}	303.0	9.0
8-10	Med. stiff brown sand	10^{-4}	351.0	ND
10-12	V. stiff lt. brown med. sand	10^{-4}	195.0	ND
12-14	V. stiff brown fine sand w/silt	10^{-4}	3.14	2.3
14-16	M. stiff grn-brn clay w/silt	10^{-8}	ND	ND
16-18	Soft wet clay	10^{-8}	ND	ND
18-20	Soft wet clay	10^{-8}	ND	ND
20-22	V. stiff brn med-coarse sand	10^{-4}	ND	ND
22-24	V. stiff brn med-coarse w/gravel	10^{-3}	6.71	ND

ND - Non-detectable level.

Table C-4. Monitoring Well 3: TCE Reduction in Soil Strata

Depth (ft)	Description of strata	Permeability (cm/s)	TCE conc., ppm	
			pre	post
0-2	M. stiff brn. fine sand	10^{-5}	10.30	ND
2-4	M. stiff grey fine sand	10^{-5}	8.33	800.0
4-6	Soft lt. brn. fine sand	10^{-4}	80.0	84.0
6-8	Lt. brn. fine sand	10^{-4}	160.0	ND
8-10	Stiff V. fine brn. silty sand	10^{-4}	ND	63.0
10-12	Silty sand	10^{-4}	NR	2.3
12-14	Soft brown silt	10^{-4}	316.0	ND
14-16	Wet green-brown silty clay	10^{-8}	195.0	ND
16-18	Wet green-brown silty clay	10^{-8}	218.0	62.0
18-20	Wet green-brown silty clay	10^{-8}	1570.0	2.4
20-22	Silt, gravel, and rock frag.	10^{-4}	106.0	ND
22-24	M. stiff lt. brn. med. sand	10^{-4}	64.1	ND

ND - Non-detectable level.
NR - No recovery of sample.

correcting for air-filled porosity, were lower than actual soil concentrations by at least an order of magnitude (see Table C-5).

Before one can attempt to make a rough estimation of the remediation time, a target value for the particular contaminant in the remediated soil must be calculated. This target concentration is calculated by using two mathematical models, the Vertical and Horizontal Spread Model and the Organic Leachate Model. (*Federal Register*, Vol. 50, No. 229, Wednesday, November 27, 1985, pp. 48886-48910.) The mathematical models allow the use of a regulatory standard for drinking water in order to arrive at a target soil concentration.

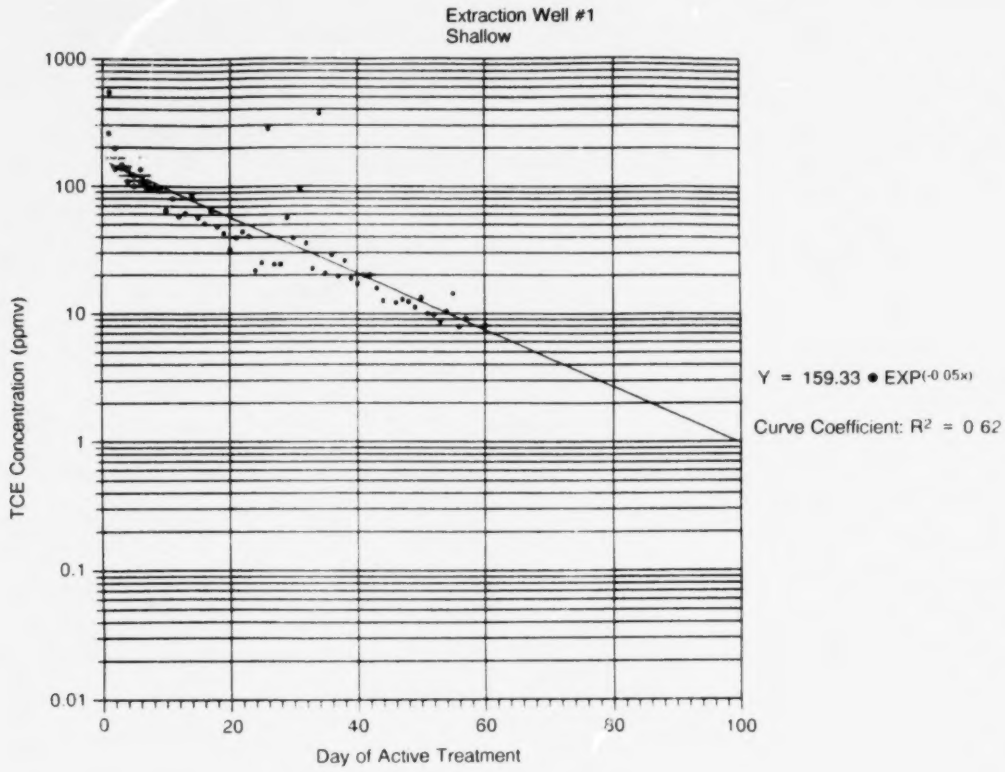

Figure C-3. Wellhead TCE concentration vs. time.

Table C-5. Comparison of Wellhead Gas VOC Concentration and Soil VOC Concentration

Extraction well	TCE concentration in wellhead gas (ppmv)	TCE concentration in soil (ppmw)	Soil concentration predicted by Henry's Law (ppmw)
1S	9.7	54.5	0.11
1D	5.6	7.2	0.07
2S	16.4	ND	0.20
2D	14.4	20.4	0.17
3S	125.0	20.9	1.53
3D	58.7	18.0	0.74
4S	1,095.6	9.1	12.49

The VHS model is expressed as the following equation:

$$C_y = C_o \, \mathrm{erf}\,(Z/(2(a_z Y)^{0.5}))\, \mathrm{erf}\,(X/(a_t Y)^{0.5})$$

where:

C_y = concentration of VOC at compliance point (mg/L)

C_o = concentration of VOC in groundwater (mg/L)

erf = error function (dimensionless)

Z = penetration depth of leachate into the aquifer

Y = distance from site to compliance point (m)

X = length of site measured perpendicular to the direction of ground water flow (m)

a_t = lateral transverse dispersivity (m)

a_z = vertical dispersivity (m)

A simplified version of the VHS model is most often used, which reduces the above equation to:

$$C_y = C_o C_f$$

where:

C_f = erf $(Z/(2(a_zY)^{0.5}))$ erf $(X/(a_tY)^{0.5})$, which is reduced to a conversion factor corresponding to the amount of contaminated soil

The Organic Leachate Model (OLM) is written as:

$C_o = 0.00211\ C_s^{0.678} S^{0.373}$

where:

C_o = concentration of VOC in groundwater (mg/L)

C_s = concentration of VOC in soil (mg/L)

S = solubility of VOC in water (mg/L)

The regulatory standard for TCE in drinking water is 3.2 ppb. This regulatory limit is used in the VHS model as the compliance point concentration in order to solve for a value of the groundwater concentration. This value of groundwater concentration is then used in the OLM model to solve for the target soil concentration.

Once the target soil concentration is determined, a rough estimation of the remediation time can be made by taking the ratio of soil concentration to wellhead gas concentration and extrapolating in order to arrive at a wellhead gas concentration at the target soil concentration. The calculated target soil concentration for this site is 500 ppbw. This corresponds to an approximate wellhead gas concentration of 89 ppb for EW1S. The equation correlating wellhead gas concentration with time (see Figure C-3) is then solved to give 150 days running time.

After 150 days the vacuum extraction system can be run intermittently to see if significant increases in gas concentrations occur on restarting, after at least a two-day stoppage. If there are no appreciable increases in gas concentration, the soil has reached its residual equilibrium contaminant concentration and the system may be stopped and soil borings taken and analyzed.

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Appendix D
Case Study D-1
Upjohn Superfund Site at Barceloneta, Puerto Rico

Introduction

The Upjohn facility is an active pharmaceutical manufacturing plant located on the north coast of the island of Puerto Rico on the boundary between the municipalities of Arecibo and Barceloneta. The Atlantic Ocean lies about 3.7 miles to the north.

A number of chemical feedstocks are stored in underground tanks at the Upjohn facility. These chemicals are processed and warehoused in plant buildings. The waste chemicals from processing are temporarily stored in underground tanks in the tank farm. It is from one of these tanks that approximately 15,300 gal of organic chemical wastes spilled in August 1982. This mixture was believed to contain 65% carbon tetrachloride (CCl_4) and 35% acetonitrile [D-1].

In January 1983, Upjohn began drilling more than 50 boreholes, ranging in depth from 30 to 200 ft, in the unsaturated zone in and around the tank farm to delineate the zones of highest contamination. Carbon tetrachloride concentrations were measured in the headspace of soil samples collected from each borehole. The investigation revealed that the CCl_4 concentrations in each borehole varied widely but, in general, tended to decrease with depth. At the soil/limestone interface, the concentrations measured by the headspace method dropped dramatically to very low levels. The exception to this pattern was for soils sampled in very deep deposits of the blanket sands at depths ranging from 100 to 210 ft below the ground surface, in which elevated levels of CCl_4 were evident.

A pilot vacuum-extraction-system (VES) was implemented at the site by Terra Vac Corp. in January 1983. The pilot system basically consisted of three vacuum extraction wells (VE), four vacuum monitoring wells (VM), one vacuum pump (VP), a cold water condenser, and a collection tank.

The primary extraction well (VE-1) was installed to a depth of 75 ft. In May 1983, three more wells and two vacuum pumps were installed. By the time the complete system was fully constructed, late in 1984, a total of 19 vacuum extraction wells had been used in conjunction with six vacuum pumps.

The initial operation of the VES used the cold water condenser to condense the liquids out of the soil gas. The collected liquids consisted of primarily water contaminated with CCl_4 and traces of acetonitrile [D-2]. The stack gas, also contaminated (mainly with CCl_4), was vented through the exhaust stack without any offgas treatment. Comparison between the amount of CCl_4 condensed from the cold water condenser and the exhaust stack indicated that the rate of CCl_4 removal through the stack was more than 1,000 times higher than collected by the condenser [D-2]. Therefore, the condenser was eliminated from the process for subsequent operations.

Most of the vacuum extraction operations relied on the air dispersion exhaust stacks. The impact of the exhausted CCl_4 on the quality of air in the tank farm was evaluated by taking vapor samples at various distances from the vent stack under different wind conditions. The field data indicated that the threshold limit value (TLV) imposed by OSHA was reached within about 30 ft of the 10-ft stack under worst conditions (i.e., low wind and high concentration). The area around the stack was roped off up to 50 ft and designated a restricted area. Consequently, studies were undertaken by Upjohn to improve the conditions. The immediate solution was to increase the stack height to 30 ft. Air quality modeling was also conducted to predict the impact of the complete (expanded) VES on air quality. These analyses showed that there was no need to incorporate any offgas treatment system prior to exhaust stacks.

For the pilot system operation, distances between the monitoring wells and the primary vacuum extraction well (VE-1) were based on preliminary calculations of the radius of influence of the vacuum. As a result, monitoring wells were spaced at 3, 5, 10, and 30 ft from VE-1 in locations accessible by a drill rig. Based on the continuous pressure monitoring at these wells, it was found that the radius of influence of the vacuum extraction wells deve-loped to only 3 ft

after 3 weeks of operation and finally stabilized at 10 ft after about 90 days.

Testing and Closure Protocols

Vacuum monitoring wells were used for vapor samples and for monitoring subsurface vacuum. The vapor samples from these monitoring wells were analyzed for CCl_4 two or three times per week, whereas subterranean pressures were recorded daily. Gas samples from the vent stacks were analyzed three times a day for CCl_4 [D-1]. Most of these samples were analyzed using the field gas chromatograph. Daily measurements of the volume of liquids collected and volumetric flow rate of vapors passing through the vacuum pump were used to calculate the daily volumes of CCl_4 extracted.

Qualitative analyses of the vented fumes and collected liquids from the vacuum extraction systems indicated the presence of CCl_4, and traces of acetonitrile, acetone, chloroform, methylene chloride and methane. Since CCl_4 was the major constituent of the waste stream, and because it is the most toxic compound of the chemicals detected, it is the only chemical that was quantitatively analyzed.

In addition to the above, soil samples were taken from test borings periodically. The "Standard Penetration Test" was used to collect the soil samples. The soil samples were analyzed in the field using the "headspace method" of analysis using a portable gas chromatograph with a flame ionization detector.

The question of when the VES had completed its job was very difficult to answer. In June 1984, Geotec, a consulting engineering company in Puerto Rico that prepared an RI/FS for the Upjohn facility, presented a criterion for the termination of the VES [D-3]. This closure criterion was based on the economic relationship between extraction from the aquifer versus extraction using the vacuum system. The allowable drinking water limit for CCl_4 at the time was 50 ppb. Based on this limit, the cost of pumping sufficient quantity of groundwater out to extract one pound of CCl_4 was estimated. Determination of the equivalent removal rate by the vacuum system at the same operating cost was proposed as the economic termination point for the vacuum system. In simple words, there is a minimum concentration in the vacuum exhaust that is as economical in removing CCl_4 from the soil as compared to pumping water contaminated with CCl_4 from the aquifer.

Such an analysis showed that in the tank farm area, the concentration of CCl_4 in the exhaust stack must go down to 2.2 µg/L before the vacuum system should be terminated. For the analytical procedure used, this translated to a non-detect level of CCl_4 in the exhaust gases.

The VES continued to operate for another two years without showing non-detectable contamination in the exhaust gauges. Therefore, Upjohn Manufacturing Co. drilled four boreholes in the area of originally high contamination [D-4]. The "Standard Penetration Test" was used for these boreholes, which varied from 40 to 105 ft, measured from grade elevation. The results showed CCl_4 to be non-detectable in all samples. Based on these results, Upjohn argued that the vacuum extraction must be accepted as complete.

Since the above proposition was based on only four boreholes, the regulatory agency did not accept it. The closure criterion established by the agency required non-detect levels of CCl_4 in all the exhaust stacks for three consecutive months. This was finally achieved in March 1988 when the VES was terminated.

Major Conclusions

The following conclusions are made from this case study.

- The VES proved effective in removing CCl_4 from the clayey soils and limestone beneath the tank farm. The action significantly reduced the amount of CCl_4 entering the aquifer from the vadose zone.
- The offgas from the vacuum extraction process, in this case, did not require any treatment before atmospheric venting.
- The concentration of CCl_4 in the offgas after any system shutdown period was found to be higher than that measured before the system shutdown.
- The demonstration of non-detect indication of CCl_4 in the offgas for three consecutive months was an acceptable criterion (by the regulatory agency) for termination of the vacuum extraction system operation.
- The VES seemed to perform well with the soil with measured permeability in the range 10^{-4}-10^{-7} cm/s.

Data Summary

Data from the Upjohn site is presented in detail in References [D-1] through [D-5]. A summary of some key data is provided below.

Soil data *before* treatment:

- CCl_4 concentrations as high as 2,200 ppm measured.
- Generally, concentration of CCl_4 decreased with depth.
- Very high concentrations found around 100 ft deep in deposits of blanket sands.
- CCl_4 concentration higher in clay as compared to that in limestone.

Soil data *after* treatment (from Reference D-4):

Bore No.	Depth of sample, ft	CCl_4	$CHCL_3$	CH_2CL_2, µg/kg
102	30	ND	ND	11.2
102	50	ND	ND	4.0
102	105	ND	ND	13.0

Offgas data:

During initial operation, concentration of CCL_4 in the offgas was as high as 70 mg/L or 10,500 ppm in air.

CCl_4 removal:

During the initial pilot operation from January 12, 1983 to April 25, 1984, approximately 8,000 gal of CCl_4 were reported to be extracted from the soil [D-2]. A cumulative amount of 17,781 gal was finally removed from the soil [D-1]. Since the initial spill was reported to be 15,300 gal, of which 65% was CCl_4, only 9,945 gal were pure CCl_4. These values indicate that the amount of CCl_4 removed by the VES was almost double what was reported as spilled in 1982. This could be explained by the following possibilities:

- Other storage tanks may have ruptured and leaked CCl_4.
- Leakage of CCl_4 may have occurred prior to 1982, but was not detected.
- The original mixture of the waste material originally spilled contained a higher percentage of CCl_4 than the reported value of 65%.

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Case Study D-2

Assessment of Vacuum Extraction Technology Application Bellview (Florida) UST Site

Introduction

The Bellview gasoline contamination site is located in Marion County in the north central portion of Florida. This site first came to the attention of the Florida Department of Environmental Regulation (FDER) in late 1982. The chronology of events at this site is shown in Table D-1.

Nature of Contamination

Previous investigations directed by the FDER indicated that an underground storage tank at the Union 76 gas station in Bellview, Fla., was a source of subsurface hydrocarbons. In December 1976, four 6-1/4 in. soil borings were made at this site, and soil samples were obtained every 2-1/2 ft. The maximum depths sampled were from 52 to 60 ft. In addition, soil samples were obtained with a hand auger at three locations in the storage tank area. All samples were analyzed onsite for gasoline components. Benzene, toluene, ethylbenzene, and xylenes (BTEX), and total volatile hydrocarbons were quantified by gas chromatography. Initial soil concentrations of BTEX were as high as 97 mg/kg, and total hydrocarbons were as high as 230 mg/kg. The highest concentrations of benzene, toluene, and xylene were observed at approximate depths of 10 to 20 ft, above a clay layer and perched water table.

Soil/site Conditions

The soil borings revealed four distinct stratigraphic zones. Clayey sands were observed from the surface to depths of 18 to 21 ft, where gumbo (a plastic clay) was encountered. The thickness of this clay layer varied from 5 to 13 ft below the surface. The silty sand layer was underlain by a weathered limestone that consisted of sand, shells, and cavities in the upper portion. Geologists noted that this limestone layer is probably part of the Upper Eocene Ocala formation. Groundwater was encountered at depths between 48 and 53 ft below the surface, while perched groundwater was observed above the clay layer in wells VE-1, ME-1, and ME-2 (Figure D-1).

Experimental/System Design

The soil VES consisted of: six extraction wells; a vacuum pump; a gas flow meter; various plumbing, valves, gauges, and sampling ports; a gasoline/water separator; and monitoring wells (Figure D-2). Pavement, which was already in place, was used as a cap. A vacuum extraction/monitoring well was installed in each borehole (see Figure D-3 for locations). The wells VE-1 and VE-2 were used primarily for subsurface hydrocarbon vacuum-extraction. Multi-level, dual-purpose wells, which could monitor the subsurface vacuum as well as extract hydrocarbons from two to three hydrogeologic zones, were installed at the other two boreholes (ME-1 and ME-2). Well ME-1, which consisted of three monitoring wells, was capable of monitoring the subsoil at depths of 13, 35, and 50 ft. Well ME-2 actually consisted of two monitoring wells, at depths of 16 and 58 ft. Each of the wells was connected to the vacuum extraction unit by way of a manifold system. So as not to interfere with the continuous operation of the service station, wellheads were installed in underground valve boxes, and the vacuum extraction manifold was covered by concrete. The system was modified to include an inline air/water separator to separate small quantities of gasoline product and water that were being extracted from the subsoils along with the hydrocarbon vapor.

Status of Experiment/Cleanup

A pilot test of the vacuum extraction operation started on January 29, 1987. By the end of February 1987, the pilot test results indicated that it was necessary to operate the system continuously in order to estimate the time required for cleanup. Due to power outages and numerous administrative problems (for example, approval of a permit to discharge extracted water), the system experienced limited operation during the months of March, April, and May. During June and July, the system was operating on a nearly continuous basis. Initial extraction rates for gasoline hydrocarbons ranged

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Table D-1. Chronology of Events at the Bellview, Florida, UST Site

Date	Events
Oct 1979-Mar 1980	Unleaded gas (10,000 gal) leaked from buried pipeline.
Aug 1982	Contamination discovered in city water-supply wells.
Oct 1982-Jun 1984	City abandoned water-supply wells; developed new wells outside city limits
Dec 1984	State conducts a contamination assessment study.
Sep 1986	State negotiates with Terra Vac to evaluate technology at this site.
Dec 1986	Terra Vac installs a series of extraction wells.
Jan 1987	Terra Vac VES begins operation.
Aug 1987	Terra Vac VES shut down after State contract expired.
Sep 1987-Oct 1987	EPA conducts vacuum extraction technology evaluation with existing system.
Sep 1988-Oct 1988	Startup and first two weeks of operation of the Terra Vac VES.

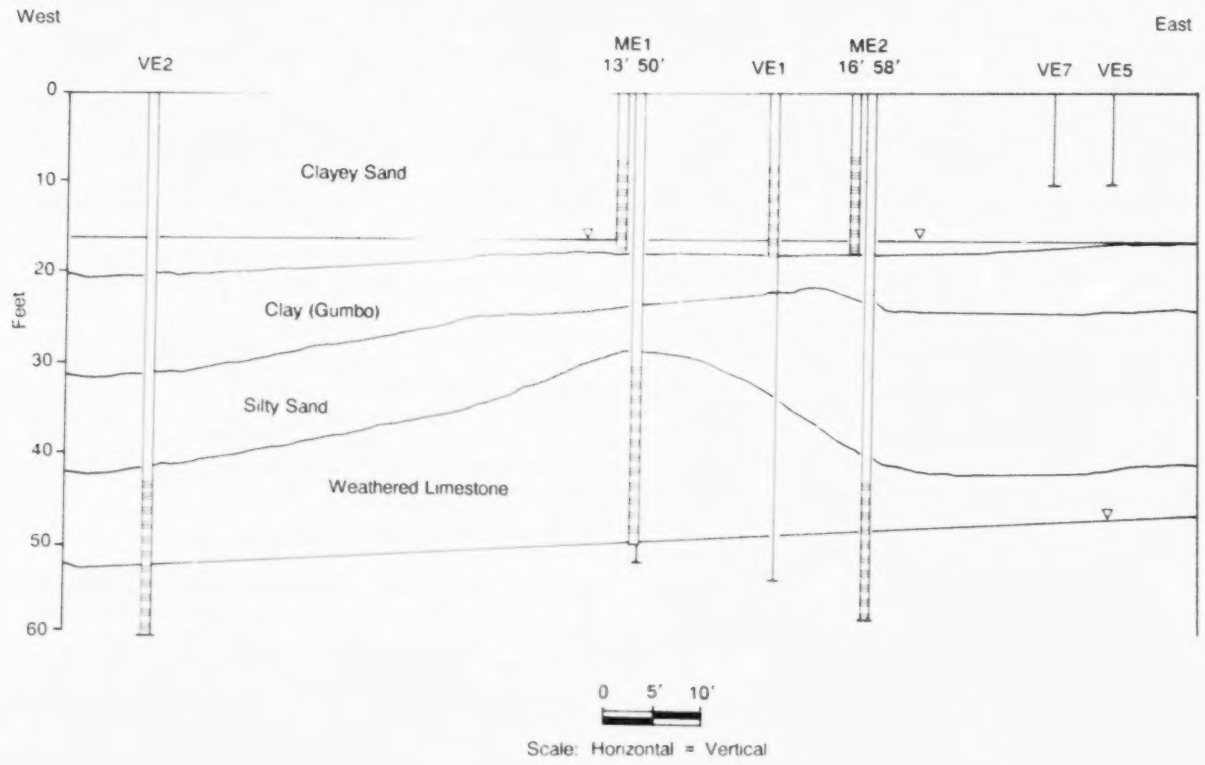
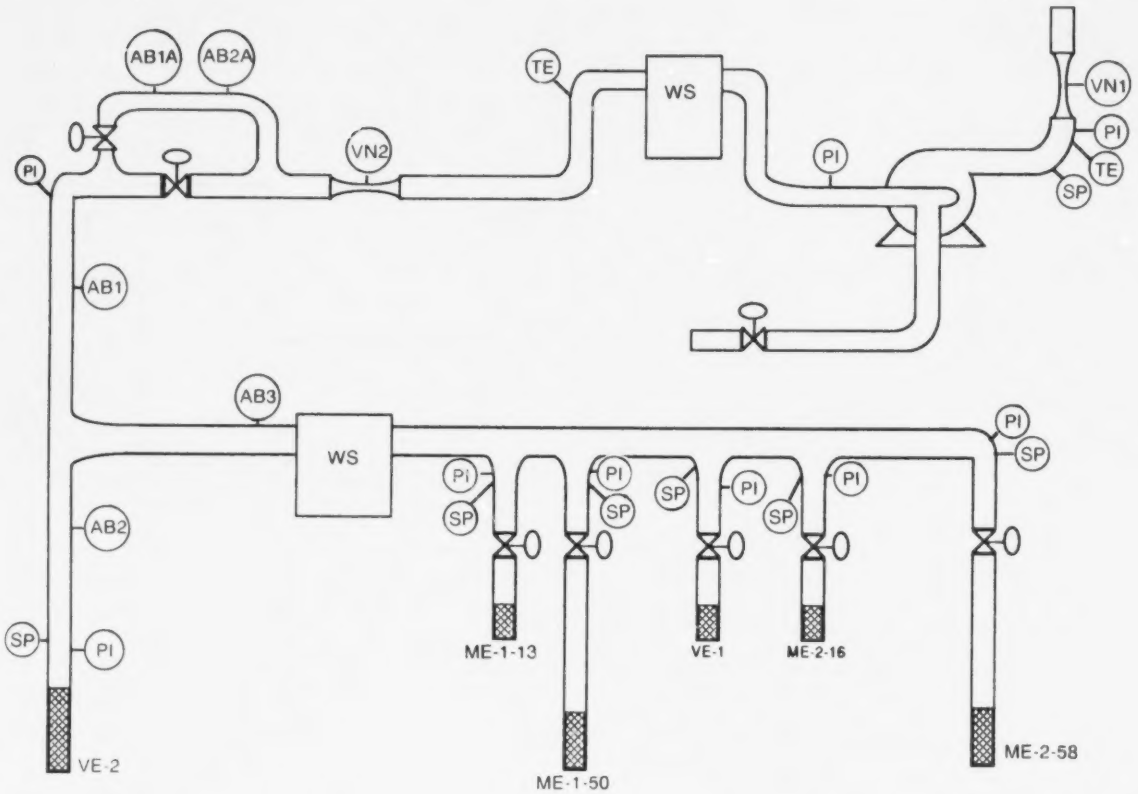


Figure D-1. Soil formations at Bellview, FL.



Legend

PI - Pressure Indicator
VN1 - Venturi Meter at Exhaust
VN2 - Venturi Meter from Wells
AB1A,AB2A - 2" Annubars
AB1,AB2,AB3 - 4" Annubars
TE - Temperature Elements
WS - Water Separator
SP - Sampling Point

Figure D-2. Process schematic at Bellview, FL.

from 295 lb (39 gal) per day in VE-1, to 1,950 lb (260 gal) per day in ME-1-50. During this pilot test, wellhead concentrations decreased with time, which would indicate the subsoils were being cleaned up. A total of 22,027 lb (2,937 gal) of gasoline hydrocarbons had been extracted from the site as of August 1987.

An independent evaluation of this system was conducted in September through October 1987 for EPA by Camp, Dresser, McKee, Inc. (CDM). Additional soil borings, soil vapor samples, and groundwater samples were collected. During this 25-day evaluation period, 22 additional pounds of BTEX

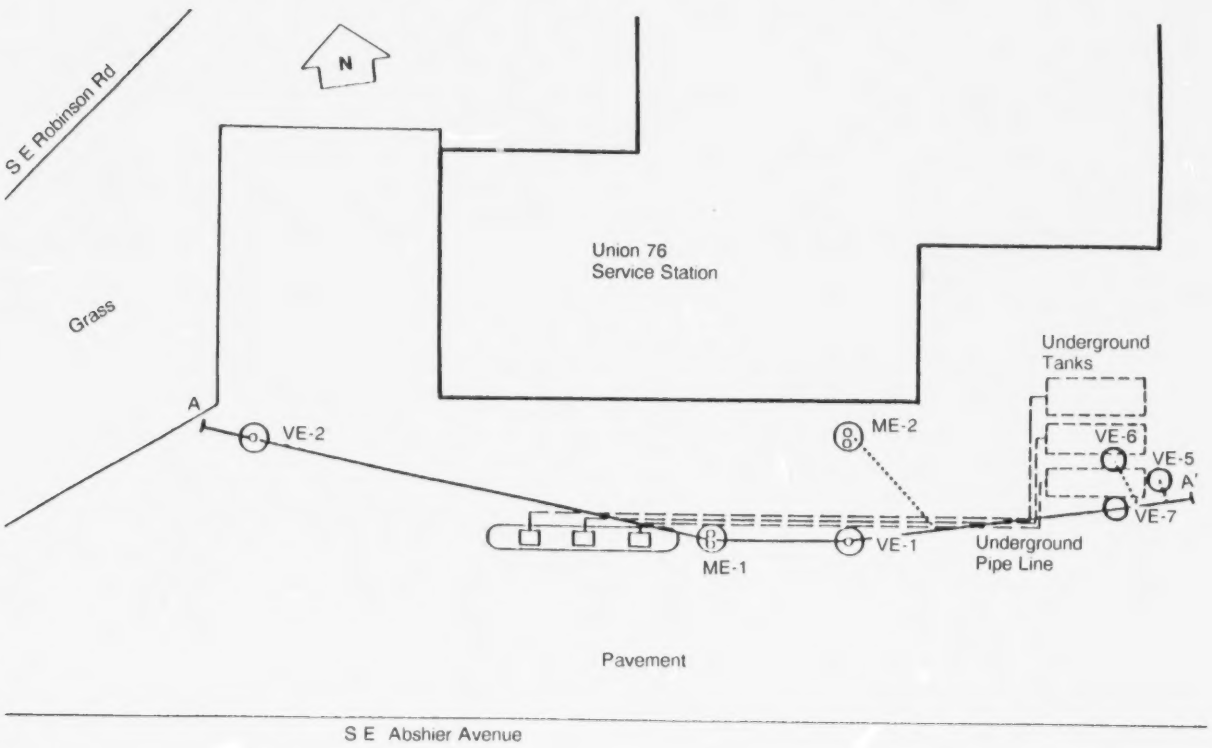


Figure D-3. Vacuum extraction well location map.

were removed. Taking into account other volatile gasoline components removed, an additional 200 lb of hydrocarbons were removed. No significant changes in the soil, soil vapor, or groundwater samples were noted.

Results and Conclusions

Based on the Terra Vac work under contract from FDER and the evaluation done by Camp, Dresser, and McKee, Inc. (under EPA contract), the latter reported the following results and conclusions.

1. Benzene, toluene, ethylbenzene, and xylenes were removed in significant quantities by the application of the vacuum extraction system to the subsurface zones. In this system, where initial soil concentrations of total BTEX ranged from 0.2 to 12 μg/g, a total of approximately 10 kg of BTEX was removed during the 25-day test period of this study.

   In addition to the BTEX removed, other major volatile gasoline components were removed. The total hydrocarbons removed was approximately 90 kg.

2. Overall removal of BTEX from the soil matrix could not be determined on an overall mass balance, based on the initial and final soil sampling, because of the heterogeneity of the BTEX contamination and the relatively small number of soil samples analyzed.

3. The extracted soil gas concentrations demonstrated a decrease in the daily quantity of BTEX extracted over the study period. The decrease in the BTEX extraction rate indicates a relative decrease in the concentration of the source material. Decreased soil gas concentrations resulted from mass transfer between the following zones: from the surface of the liquid to the bulk surface of the soil to the internal pore space. The rate limiting step is the diffusion of the contaminants from the pores.

4. The groundwater quality was not affected by the vacuum extraction system, even though a

measurable air flow was observed within the vicinity of high groundwater contamination. The variations in groundwater quality over the vacuum-extraction system operation can be attributed to seasonal fluctuations in the water table and migration of contaminants away from the source area.

5. Based on a statistical comparison to the soil gas data collected in the initial and final soil gas surveys, the mean concentrations of total BTEX were within the same concentration range. The mean soil concentrations for total BTEX from the initial and the final soil gas survey were in the range of <0.2 to 0.3 ppmv. The results of the surveys demonstrate no statistical difference between the two data sets. However, it is clear that soil gas concentration levels were near or below detectable limits for BTEX.

6. A statistical comparison of the initial and final soil-sampling analyses demonstrate no difference between the two data sets for toluene, ethylbenzene and total xylenes. The benzene concentrations demonstrated a real difference between the initial and final data sets, in the increased levels of the final soil-sampling data. The mean concentration for each individual BTEX component was in the range 0.2 to 1.3 µg/g. Concentrations were not observed above 6.0 µg/g.

7. Monitoring wells MW-2, MW-6, and MW-7 all had measurable concentrations of total BTEX for both groundwater sampling events. All other monitoring wells were near or below the detection limit for each BTEX component of 1.0 µg/L. MW-6 contained the highest BTEX concentration of about 10,400 µg/L in the initial sampling program and about 10,700 µg/L in the final sampling program. A comparison between each BTEX component showed no statistical difference between the two data sets for either MW-6 or MW-7 groundwater quality.

8. The quantity of contaminants extracted from each extraction well varied greatly over the spatial distribution of the site. In general, the shallow extraction wells located in the clayey sands exhibited significantly higher extracted soil gas concentrations than observed from the deep extraction wells located in the weathered limestone formation. However, the deep extraction wells exhibited significantly greater air flow rates than the shallow extraction wells when the same vacuum was applied at the wellhead. The net result of this combination of soil/gas concentration and the air flow rate, the BTEX extraction rate, demonstrated that the deep extraction wells extracted more mass of contaminants (approximately 70% of the total mass extracted) than the shallow extraction wells did, even though the relative contamination was greater in the clayey sands.

9. The quantity of air extracted from the extraction wells varied greatly with the soil type under the same applied vacuum. In general, each shallow extraction well yielded approximately 570 L/m (20 cfm) of air at applied wellhead vacuums of about 130 cm (50 in.) of water. These wells were screened at the interface of clayey sand and gumbo clay formations.

   Two of the deep extraction wells each yielded approximately 8,500-11,300 L/m (300-400 cfm) of air at applied vacuums of about 80-100 cm (30-40 in.) of water. These wells were screened in a weathered limestone formation where significant cavities were observed.

10. The transmission of the applied wellhead vacuum through the soil matrix was also affected by the soil type. The cone of influence or convective air-flow boundary was significantly less in the clayey sands than the weathered limestone. The vacuum influence in the clayey sands extended approximately 6 m where about 1% of the wellhead vacuum was observed. The vacuum influence in the weathered limestone due to the deep extraction wells extended about 30 m in the northwest direction (where about 3% of the wellhead vacuum was measured) and more than 30 m in the southeast direction (where about 17% of the wellhead vacuum was observed).

    When a vacuum was applied at Well VE-1 in the clayey sands, an induced vacuum was also observed in the weathered limestone (where about 8% of the wellhead vacuum at VE-1 was observed) more than 60 meters away in the southeast direction. This influence between the two geologic formations confirms the communication between the two formations.

11. The contaminant extraction rates from each well, as well as the combined gas flow, decreased over the 25-d study period for each BTEX component and total hydrocarbons. The hydrocarbons extraction rate from all the extraction wells was about 6.0 kg/d at the startup of the field study and quickly decreased within days, to an average extraction rate of about 3.0 kg/d.

12. The deep extraction wells located in the limestone extracted a greater fraction of total hydrocarbons as compared with the total BTEX components than the shallow extraction wells

located in the clayey sands. The deep extraction wells extracted a total mass ratio of hydrocarbons to BTEX of about 17 to 1, whereas the shallow extraction wells extracted a total mass ratio of hydrocarbons to BTEX of about 6 to 1.

13. The fraction of BTEX concentrations compared to the total hydrocarbon concentrations in the clayey sands more closely matches the relative BTEX fraction in pure gasoline than those observed in the weathered limestone. The residual BTEX in the weathered limestone seems to contain a disproportional amount of xylenes.

14. The concentration ratio between each BTEX component varied systematically over the time period of the EPA field investigation of the vacuum extraction system operation. Benzene and toluene, the more volatile components of the BTEX fraction, decreased in the extracted gas concentration at a faster rate than the less volatile components, ethylbenzene and xylenes, from several of the shallow extraction wells. This indicates that the relative amounts of the more volatile components are being removed from the soil matrix to a greater degree than the less volatile components.

Cost Evaluation

The cost figures reported by CDM include capital costs of $106,100 and operating and maintenance costs of $68,000, for a total of $174,100.

No attempt has been made by CDM or any other contractor to determine the amount of soil that was contaminated by this leaking gasoline underground-storage tank. However, an order of magnitude estimate of the amount of contaminated soils at the Bellview site could be between 3,000 and 10,000 yd^3. Based on these estimates, the total cost, i.e., capital and operating costs, to remediate these soils in a one-year period would be in the range of $20 to $60/$yd^3$. However, these costs depend on the required cleanup goals of the site and will increase if longer treatment periods are required to further reduce the contamination level.

The above costs do not include extraction air treatment as this was not required at the Bellview site. However, if air treatment was required and it was assumed that a carbon adsorption system would be used, the costs of a carbon adsorption system would more than double the total vacuum extraction system costs. Actual costs of the carbon adsorption system would depend on the carbon usage rates of the extracted air flow.

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Case Study D-3

Verona Well Field (Michigan) Superfund Site Soil Remediation Using Large Scale Vacuum Extraction

Introduction

As part of the USEPA's total site remediation strategy, a soil vacuum extraction system (VES) was selected to remediate soils at the Verona Well Field/Thomas Solvents Raymond Road Facility Superfund site. In 1987 Terra Vac Corp. was contracted to design, install, and operate the VES in conjunction with other already ongoing work at the site, which included the recovery and treatment of groundwater.

The well field is located in Battle Creek, Michigan and supplies potable water to over 35,000 consumers. In 1981 VOCs were discovered to have contaminated both private and city wells, and the well field was placed on the National Priorities List during 1982. Subsequent USEPA investigations revealed a former solvent storage and transfer facility was one of the sources of the groundwater contamination. The site included twenty-one underground storage tanks, some of which had previously leaked chlorinated and nonchlorinated solvents.

A Record of Decision was signed in 1985 specifying soil vacuum extraction as the Remedial Measure for treatment of soils at the former solvent facility, to eliminate one source of groundwater contamination. The underground storage tanks were scheduled for removal after completion of soil treatment by vacuum extraction. Design and construction of the VES began in September 1987. Construction was completed in March 1988, with full-scale operations commencing thereafter.

This project is ongoing. The following is a summary of the progress made thus far and preliminary conclusions.

Vacuum Extraction System Design

The major system design criteria are the following:

Hydrogeologic Considerations--
The geology at this site is composed of unconsolidated material derived from glacial outwash and floodwater channel deposits, overlying the Marshall Formation, a sandstone bedrock. The soils at the site consist of fine-to-coarse grained sand with localized lenses of gravel and silt. Groundwater fluctuates between 20 and 30 ft below the surface and a localized cone of depression is present due to groundwater extraction wells both on and off site.

Nature of Contamination--
Previous investigations indicated the presence of VOCs, mainly chlorinated hydrocarbons, aromatics, and ketones. Soil concentrations as high as 1,800 mg/kg of specific contaminants were reported. Contaminants included TCE, PCE, TCA, methylene chloride, xylenes, DCA, acetone, toluene, and ethylbenzene. Contamination was indicated throughout the unsaturated zone, with the possibility of nonaqueous phase liquid (NAPL). An area of approximately 35,000 ft^3 as addressed by the VES design.

Cleanup Criteria--
Achievement of cleanup criteria will be verified by posttreatment soil sampling and analysis. The specified cleanup criteria requires all soil samples to be less than 10 mg/kg total VOCs, with no more than 15% above 1 mg/kg total VOCs.

VES Emissions Controls--
Limits placed on a number of VOCs present required the design and operation of an activated carbon system. Allowable concentration at the VES discharge stack were:

tetrachloroethylene	0.0024 mg/L
trichloroethylene	0.0073 mg/L
methylene chloride	0.0406 mg/L
chloroform	0.0008 mg/L
carbon tetrachloride	0.0016 mg/L
vinyl chloride	0.0162 mg/L
benzene	0.0057 mg/L

Underground Tank Impacts--
Twenty-one underground tanks at the site are not scheduled for removal until soil treatment is complete. The impact of the tanks on the subsurface

flow regime, and on subsurface vacuum levels was evaluated, and is reflected in the VES design.

Vacuum Extraction System Implementation

A two-phase approach was used for the implementation of the VES design. The first phase was a pilot phase during which the preliminary design was confirmed. The second phase of implementation, full-scale system design and construction, started immediately after data from the pilot phase were evaluated.

Four vacuum extraction wells were installed in October of 1987 to serve as a pilot phase for the soil remediation. During the installation of the vacuum extraction wells, soils were sampled and analyzed using an onsite gas chromatograph and the headspace method to quantify the distribution of VOCs in soils in the area of the pilot wells. Residual VOC concentrations in the area of the four pilot test wells ranged as high as 1,380 mg/kg. The soil concentration data was used to confirm the design basis of the vacuum extraction system, to determine screened intervals, and was later used to correlate monitoring results with soil concentrations. In addition, a soil gas survey was performed throughout the site, including support areas, to further delineate the real extent of soils to be treated by the VES.

Each well consisted of a 4-in. PVC slotted-well screen and riser, a silica sand pack in the annular space, and bentonite and grout seals to make the wells suitable for vacuum service Wells later installed as part of the full-scale system included both 4-in. wells with slotted screen and 2-in. continuous wire wrapped screens. An aboveground PVC piping manifold was connected to the equipment used during the pilot phase, which consisted of an air/water separator, a 30-hp vacuum extraction unit, and an emissions control system containing four 1,000-lb canisters of vapor-phase activated-carbon. (Two in primary service, and two in backup service.) A 30-ft-high discharge stack was constructed.

After startup of the pilot phase VES, each well was developed individually. In general, during the development period of a vacuum extraction well, the soils surrounding the well are dried, air flow paths are developed, a well's maximum radius of influence is reached, and steady state flows are established. For the wells at this site, the development period for each well was very short, on the order of 1 to 4 hours.

During all phases of operation of the VES, individual wellhead VOC concentrations and other vapor stream concentrations throughout the VES were determined by onsite gas chromatography. Air flow rates were measured using self-averaging pitot tubes, or rotameters, depending on flow rates. The radius of influence for each well was determined by measuring subsurface vacuums using piezometers and other VES wells at different distances from the vacuum extraction well being developed.

The radius of influence for the pilot phase VES wells was determined to be in excess of 75 ft. As an example, a subsurface vacuum of 1/4 in. of water was measured 95 ft away from VE-1, one of the first wells to be developed, shortly after startup.

After intermittent operation of the pilot phase VES wells for approximately 70 h over a period of 15 d, construction of the full scale system was started. The full-scale VES began operations in March 1987. A total of 23 vacuum extraction wells were installed at the site. The location and number of wells reflected pilot-phase experience, accounted for the effect on subsurface airflows of the underground tanks, and provided operating flexibility to ensure all affected areas would be treated.

The vacuum extraction system consisted of two vacuum units. The vapor-phase activated-carbon system was enlarged to 8 canisters with 4 in primary service, and 4 in backup service. Carbon adsorption efficiency was determined to be equivalent under positive pressure and vacuum during the pilot phase, therefore the full-scale system was constructed with activated carbon under vacuum to minimize leaks, and to eliminate possible emissions of contaminant-laden air to the atmosphere.

Although the need to change frequently and regenerate activated carbon offsite during the first 10 days of operation dictated attended operation, the VES was designed and constructed for unattended operation. Instrumentation and controls installed included: pressure, flow and temperature indicators; a high-water-level shutdown in the air/water separator, a carbon monoxide monitor and shutdown in the activated carbon system, high temperature shutdowns, and an online PID VOC monitor for detecting primary-carbon system breakthrough. Vapor samples were analyzed with the onsite gas chromatograph at various VOC levels to determine the PID monitor's response to specific compounds. When VOC concentrations entering the backup carbon system reached a predetermined setpoint on the PID monitor, the VES system was automatically shut down. The vacuum extraction system is shown schematically in Figure D-4.

To date, the vacuum extraction system at this Superfund Site has operated for approximately 55 days. Onsite gas chromatography has been used to monitor wellhead VOC concentrations and extraction rates. The logistics of changing, transporting, and regenerating activated carbon

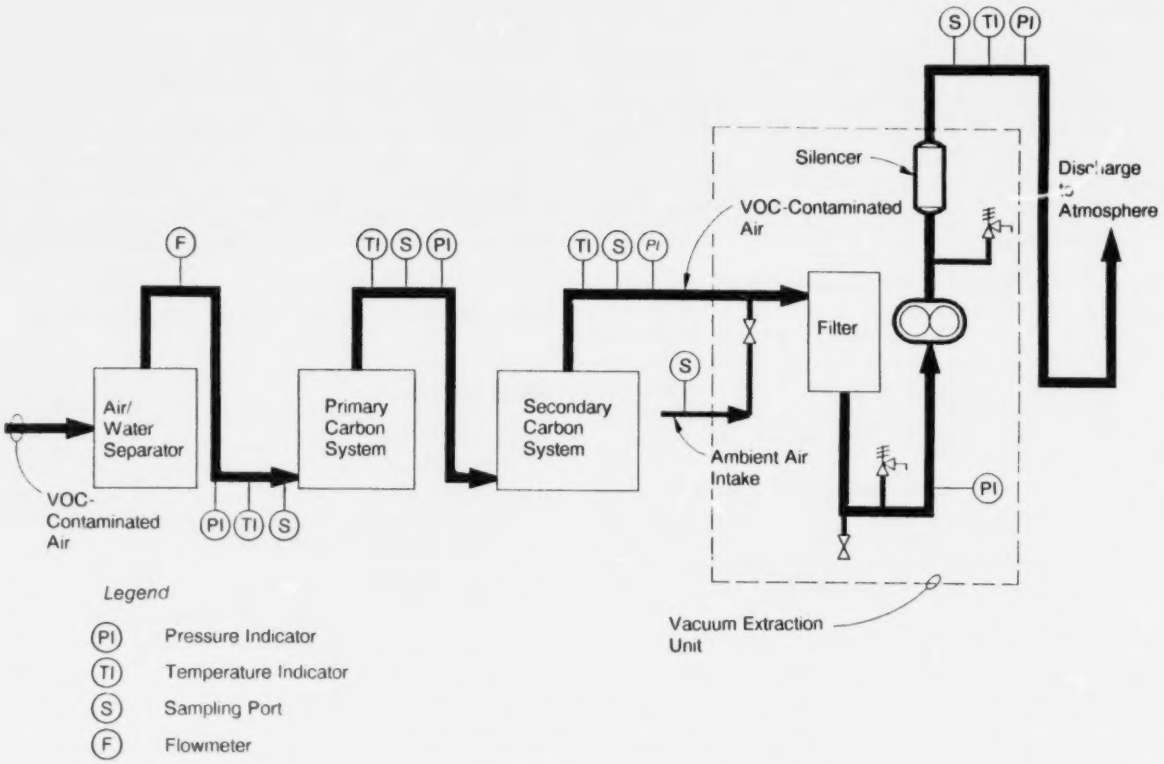

Figure D-4. Schematric of VES at Verona, MI.

offsite have been the limiting factor for VES operations.

Field Analytical Program

An onsite laboratory was established to provide a rapid screening of both soil and extracted vapor samples. A Hewlett-Packard 5890A gas chromatograph with dual flame ionization detectors and capillary columns was coupled with a personal computer and chromatography software. Twenty-two compounds were identified as substances of concern and methodology was developed to analyze for these compounds. Chlorinated hydrocarbons (including TCA, TCE, PCE, and vinyl chloride), aromatics, (including benzene, toluene, and xylenes) and ketones (acetone, MEK, and MIBK) were the three major groups of compounds analyzed for.

The minimum detection limits (MDLs) for each compound of interest was determined. The MDLs ranged from 0.0001 to 0.0080 mg/L and normally showed more sensitivity for aromatic compounds than chlorinated compounds. Calibration was accomplished by injection of a certified standard gas. A QA/QC program was implemented using standards, replicates, duplicates, and blanks.

During well installation, more than 200 soil samples were screened by the onsite gas chromatograph, providing field data to confirm VES well design. The onsite laboratory routinely analyzed vapor samples for the purposes of tracking VOC extraction rates, verifying activated carbon breakthrough, quantifying stack VOC discharge rates and monitoring the progress of soil treatment.

Vacuum Extraction System Performance

During the operation of the vacuum extraction system, extracted airflows from individual VES wells have ranged from 60 to 165 cfm, with wellhead vacuums ranging from 2 to 5 in. of mercury. Individual well extraction rates were determined for all VES wells using measured flow rates and VOC concentrations determined by onsite gas chromatography. A total of VES extraction rate was also routinely determined. Total VES extraction

rates were confirmed by offsite analysis of spent carbon.

Individual initial VES well extraction-rates ranged from 4,400 lb/d to 23 lb/d. The highest individual well extraction rate, 4,400 lb/d, was measured during the pilot phase. TCA was extracted at a rate of 1,316 lb/d, with TCE, PCE, toluene, methylene chloride, and xylenes all being extracted at rates in excess of 100 lb/d. Figure D-5 shows the relative VOC extraction rates in lb/d of one well, VE-2.

Individual wellhead VOC concentrations declined during the operation of the VES. Since the concentration of VOCs in the airstream extracted from a VES well is representative of the aggregate soil-gas concentration within a well's radius of influence, the wellhead concentrations provide an indication of the degree of cleanup being achieved.

Well VE-2 had the highest initial wellhead concentrations, which were measured to be in excess of 250 mg/L total VOCs during well development. After approximately 55 days of VES operations, wellhead concentrations decreased to below 10 mg/L.

At other sites where vacuum extraction has been applied, the wellhead concentration vs. time data follows a characteristic curve. Preliminary evaluation of the data from this Superfund Site indicates that soil cleanup objectives will be attained in approximately 100 days of VES operation.

To date, more than 28,000 lb of VOCs have been extracted by the vacuum extraction system, representing approximately 55 days of operating time for the VES, as shown in Figure D-6. The total amount of VOCs extracted is based on monitoring of the system using onsite gas chromatography. Offsite analysis of spent carbon confirms that the onsite monitoring is accurate to within approximately 5%.

Conclusions

Since this project is still in progress, very specific and definitive conclusions cannot yet be drawn. However, based on the evaluation of operating data from the application of a large-scale vacuum extraction system to the VOC contaminated soils at this Superfund Site, vacuum extraction has been successful in significantly reducing VOC concentrations in the soil. Although factors not associated with performance of the VES have resulted in approximately one year of activity at the site, the short VES operating timeframe (approximately two months) has resulted in the safe recovery of VOCs that would take many years to recover using groundwater recovery and treatment only.

Cost information on this project was unavailable.

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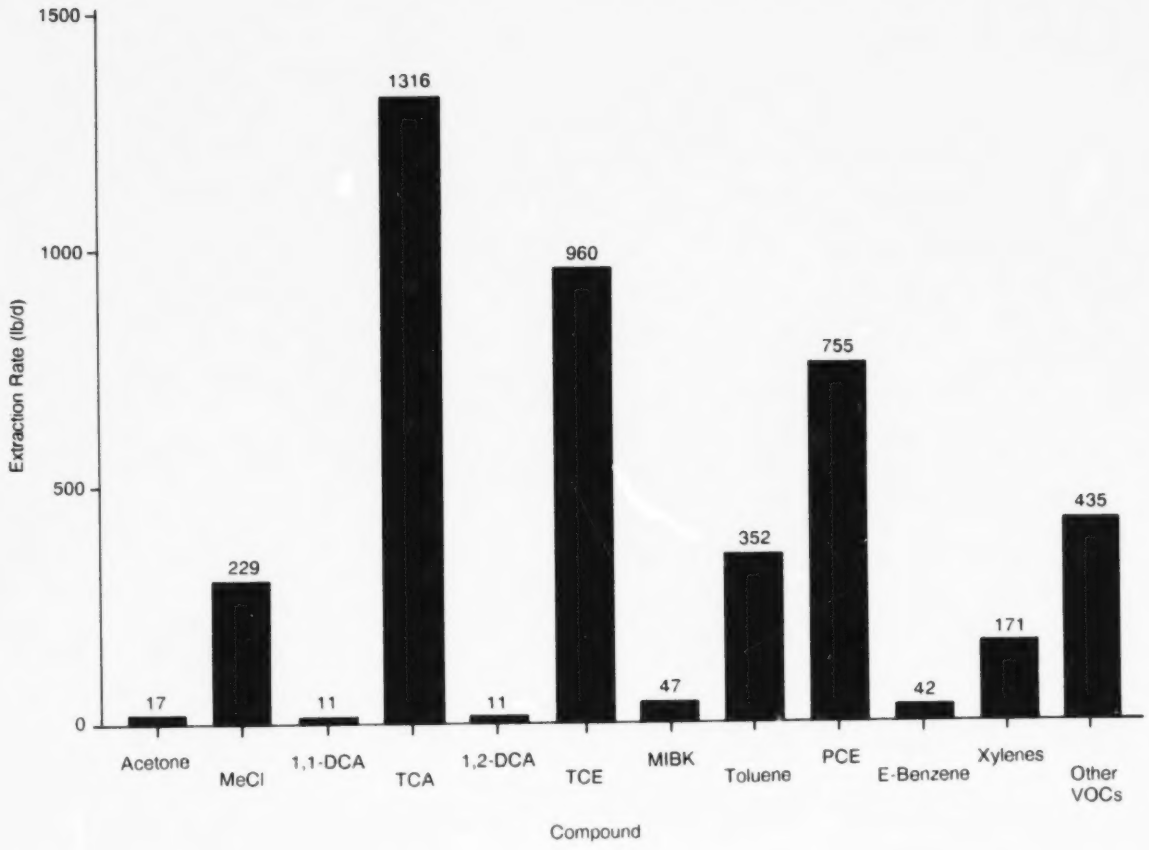

Figure D-5. Relative extraction rates.

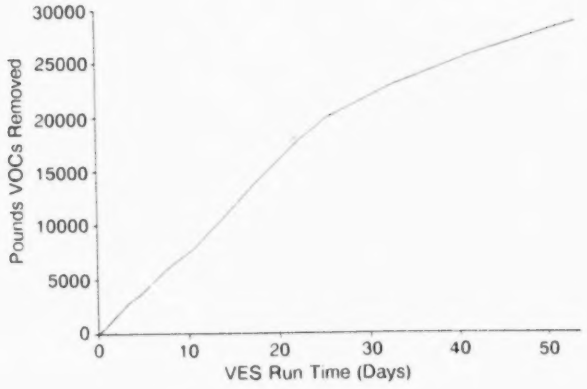

Figure D-6. Total lb VOC extracted.

Case Study D-4

Terra Vac Vacuum Extraction Technology Application at Tyson's Superfund Site Upper Merion Township, Pennsylvania

Introduction

Tyson's site is an abandoned septic waste and chemical waste disposal site within a sandstone quarry that was operated from 1962 to 1970. The site, located in Upper Merion Township, Montgomery County, Pennsylvania, is approximately four acres and consists of unlined lagoons. It is bordered on the east and west by tributaries of the Schuylkill River, on the south by a steep quarry highwall, and on the north by a Conrail railroad switching yard. The group of PRPs for the site is headed up by the Ciba-Geigy Corporation.

Site Contamination

The soils in the lagoons are contaminated with volatile organic compounds and with lesser levels of contamination of semi-volatile compounds. Table D-2 shows the analysis of subsurface soil samples from the lagoons collected by Baker/TSA for the onsite remedial investigation (RI) in 1984.

Chronology of Events

From 1960 to 1970 the site was owned by companies owned by Franklin P. Tyson and by Fast Pollution Treatment, Inc. The current owner of the land, General Devices, Inc., had owned the stock in Fast Pollution Treatment, Inc. along with Franklin P. Tyson. In 1969 General Devices purchased the property from Fast. The Pennsylvania Department of Environmental Regulation (DER) ordered the site closed in 1973 and the lagoons were emptied of standing water, backfilled, vegetated, and the standing waste was transported offsite. In 1983, the EPA Emergency Response Team conducted a preliminary investigation of the site in response to an anonymous citizen complaint. In March 1983 EPA instituted immediate removal actions, including a leachate collection system, an air-stripping leachate-treatment system, an activated-carbon offgas treatment-system for the air stripper, and installation of monitoring wells.

Table D-2. Maximum and Frequency Detected for Organic Compounds Analyzed in Subsurface Soil Samples from the Former Lagoons, Collected by Baker/TSA (Onsite RI) (mg/kg, dry weight basis)

Compound	Maximum	Frequency detected
Semivolatiles		
2-Chlorophenol	7	2 - 23
2,4-Dimethylphenol	7	5 - 23
Phenol	240	6 - 23
2-Methylphenol	22	6 - 23
4-Methylphenol	18	6 - 23
1,2,4-Trichlorobenzene	210	14 - 23
2-Chloronaphthalene	0.57	1 - 23
1,2-Dichlorobenzene	140	14 - 23
1,4-Dichlorobenzene	1.1	3 - 23
Naphthalene	0.92	2 - 23
Nitrobenzene	23	4 - 23
N-Nitrosodiphenylamine	1.3	2 - 23
Bis(2-ethylhexyl)phthalate	14	4 - 23
Di-n-butyl Phthalate	130	14 - 23
Di-n-octyl Phthalate	11	1 - 23
2-Methylnaphthalene	12	1 - 23
Volatiles		
1,2,3-Trichloropropane	25,000*	18 - 23
Ethylbenzene	13,000	18 - 23
Tetrachloroethene	13,000	4 23
Toluene	8,800	12 - 23
Trichloroethene	0.82	1 - 23
o-Xylene	27,000	20 - 23
Chlorobenzene	6.4	1 - 23

*Tentatively identified compound, concentration estimated.

Various studies were initiated, including an RI/FS by Michael Baker, Jr., Inc. under subcontract to NUS Corp. in 1984.

In January of 1985 EPA issued a ROD for the site using excavation and removal of surficial soils to a RCRA landfill. EPA however did not study the deep aquifer and as a result, was not able to identify the principal pathway of contaminant migration. A subsequent comprehensive Feasibility Study was prepared for Ciba-Geigy by ERM, Inc. and as a result of this study and pilot demonstrations done by Terra

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Vac in the field in 1986 and 1987, Terra Vac was awarded the contract for the complete remediation of the Tyson's Superfund site.

Terra Vac's Pilot Demonstration

Terra Vac installed 4 vacuum-extraction wells into the surficial materials to the top of the bedrock surface in the east lagoon area. A fifth area (SB-2) was installed in a bedrock area, 40 ft north of VE-1. Bedrock is encountered 11 ft below the surface at this location. The ground water table at SB2 was 28 ft below the surface. Vapors were extracted from the bedrock formation between the top of rock at 11 ft and the water table at 28 ft below the surface. The results and conclusions of Terra Vac's 21-day pilot test were:

1. Flowrates from vacuum extraction wells increased significantly as the wells were developed with the vacuum extraction process, up to 165 cfm from an individual well.

2. The radius of influence of the vacuum extraction wells was developed to about 40 ft in the subsoils of the east lagoon area.

3. VOCs detected in extracted vapors include benzene, toluene, xylenes, TCE, PCE, and TCP, at rates up to 154 lb/d.

4. About 1,330 lb of VOCs were extracted from the subsoils and treated with activated carbon during the pilot test.

5. The highest recovery rates were observed for xylenes, toluene, and TCP.

6. Vacuum extraction of VOCs from the bedrock formation beneath the contaminated subsoils successfully recovered about 15 lb/d and induced a radius of influence of about 100 ft within the bedrock and into the subsoils of the lagoon area.

Terra Vac's Full-Scale Remediation of Tyson's

Terra Vac has installed and has been operating, since November 1988, a full-scale remediation facility for the Tyson's Superfund site. Almost 100 extraction wells have been installed, consisting of 81 shallow-soil wells, 9 deep-rock wells, and 7 shallow-rock wells. The system can handle an air flow rate of 9,000 scfm in two parallel branches. There are 4 primary activated-carbon canisters and 2 secondary or guard canisters. The spent activated carbon is regenerated onsite by steam in a batchwise operation.

The vacuum system has a total of 4 blowers, 2 with 700-hp motors and 2 with 250-hp motors. The activated carbon canisters are on the discharge side of the blowers. Water treating facilities are located on the site and consist of an air stripper with an activated carbon canister for the offgas. Laboratory analyses are performed in a permanent onsite laboratory. The system is operated continuously and is manned by 3 people per shift, 24 h/d. A total of 20 people are working at the site during the daytime hours performing various monitoring functions.

Cost information on this project was unavailable.